UNIVERSITI PUTRA MALAYSIA

EARLY DETECTION OF Ganoderma boninense *IN OIL PALM SEEDLINGS USING HYPERSPECTRAL IMAGES AND MACHINE LEARNING CLASSIFICATION TECHNIQUES*

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By

AIMAN NABILAH BINTI NOOR AZMI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

January 2021

I dedicated this thesis to my parents. I hope that this achievement will complete the dream you had for me all those many years ago when you chose to give the best education you could.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

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January 2021

Chair : Siti Khairunniza binti Bejo, PhD
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Basal stem rot (BSR) caused by *Ganoderma boninense* (*G. boninense*) fungus is one of the most destructive diseases of oil palm plantations in Southeast Asia that resulted in losses up to USD500 million annually. Besides mature trees, seedlings are also susceptible to *G. boninense* infection after being transplanted into a plantation. Therefore, early detection, timely prevention and control are crucial because trees with less than 20% infection can still be treated. This study focuses on early detection of *G. boninense* in oil palm seedlings based on the physical growth of seedlings, spectral reflectance of leaves and machine learning classification. Twenty-eight oil palm seedlings aged five months old were used whereby 15 of them were inoculated with the *G. boninense* pathogen. The physical growth of the seedlings was monitored for every two weeks, and parameters recorded were fronds count, chlorophyll content, height, and girth. The physical growth did not provide any significant differences between the uninoculated (H) and inoculated (U) seedlings throughout the study, which indicate no BSR symptoms had appeared; however, the H obtained marginally higher measurements in most weeks. After 20 weeks of inoculation, spectral reflectance oil palm leaflets taken from fronds 1 (F1) and 2 (F2) were obtained using Cubert FireflEYE S185 hyperspectral camera with wavelength ranging from 450 to 950 nm. The differences between H and U were observed in the NIR and red-edge spectrum for reflectance and first derivative spectra, respectively. Thirty-five bands were found significant for reflectance and 14 bands for first derivative spectra. The bands were later used as input parameters to develop F1, F2, a combination of F1 and F2 (F12), F1 derivative ($F1_{dev}$), F2 derivative ($F2_{dev}$), and F12 derivative ($F12_{dev}$) classification models, i.e., decision trees, discriminant analysis, logistic regression, naïve Bayes, support vector machine (SVM), k-nearest neighbor, and ensemble. These bands were optimised according to the classification accuracy achieved by the models. The result showed that the acceptable

number of bands to develop classification models was 11 bands which obtained accuracies of 100% (F1), 92% (F2), 95% (F12), 97% ($F1_{dev}$), 90% ($F2_{dev}$) and 93% ($F12_{dev}$) which considered the highest of its classes. Overall, 11 bands of F12 provided near good linear SVM model with 95% accuracy and a kappa value of 0.9; it was considered the best model since it did not require complex pre-processing to separate F1 and F2. This information is useful in aerial-view applications when applying an unmanned aerial vehicle (UAV) for image acquisition since both fronds can be clearly seen from the top-view image hence could expedite the detection of the BSR disease.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Sarjana Sains

PENGESANAN AWAL *Ganoderma boninense* PADA ANAK POKOK KELAPA SAWIT MENGGUNAKAN IMEJ HIPERSPEKTRAL DAN TEKNIK PENGELASAN MESIN PEMBELAJARAN

Oleh

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Reput pangkal batang (BSR) yang berpunca daripada kulat *Ganoderma boninense* (G. boninense) adalah salah satu penyakit yang paling bahaya pada ladang kelapa sawit di Asia Tenggara yang mengakibatkan kerugian hingga USD500 juta setiap tahun. Selain pokok matang, anak pokok juga berpotensi untuk terkena jangkitan G. boninense setelah dipindahkan ke ladang komersial. Kajian intensif telah dilakukan untuk mencari teknik yang mudah untuk mengesan tahap jangkitan awal, dan potensi untuk menggabungkan imej dengan maklumat spektral telah dikenalpasti dengan menggunakan penginderaan jauh hiperspektral. Sebelum imej hiperspektral diperoleh, pertumbuhan fizikal anak pokok kelapa sawit dipantau sepanjang 20 minggu inokulasi dengan patogen G. boninense kerana jangkitan G. boninense boleh memberi kesan pada pertumbuhan fizikal kelapa sawit apabila jangkitan semakin parah. Parameter fizikal yang telah direkodkan adalah bilangan pelepah, kandungan klorofil daun, tinggi anak pokok dan lilitan batang. Hasil kajian menunjukkan bahawa secara purata, anak pokok yang tidak diinokulasi (H) lebih tinggi 2.30 cm, lebih lebar 1.35 mm dan mempunyai lebih banyak pelepah daripada anak pokok yang diinokulasi (U). Bagaimanapun, parameter ini tidak memberikan perbezaan yang signifikan secara statistik di antara H dan U, walaupun anak pokok H memperoleh bacaan yang lebih tinggi pada kebanyakan minggu. Pada 20 minggu inokulasi, imej hiperspektral anak pokok diperoleh untuk mengkaji pantulan spektral daun daripada pelepah nombor satu (F1) dan dua (F2) pada keadaan H dan U. Penyingkiran kebisingan dilakukan untuk membersihkan 558 dan 564 pantulan spektra daripada F1 dan F2, masing-masing daripada data yang tidak diingini. Pantulan spektra kemudian dipuratakan dan diplot di mana perbezaan antara H dan U dilihat jelas dalam spektrum inframerah dekat (NIR) untuk spektra pantulan dan rantau tepi merah untuk spektra terbitan pertama. Berdasarkan purata spektra, sejumlah 35 dan 14 jalur dikenalpasti signifikan secara statistik untuk F1, F2 dan gabungan F1 dan F2 (F12) dalam pantulan dan turunan pertama, masing-masing. Jalur signifikan yang telah dikenalpasti digunakan sebagai parameter input untuk menbangunkan model klasifikasi mesin pembelajaran. Model klasifikasi yang terlibat adalah pokok keputusan, analisis diskriminan, regresi logistik,

naïve Bayes, mesin vektor sokongan (SVM), k-nearest neighbor, dan ensemble. Jumlah jalur signifikan ini dioptimumkan berdasarkan ketepatan klasifikasi yang dicapai oleh model. Hasilnya, bilangan jalur signifikan untuk pantulan yang dioptimumkan adalah 18, 14, 11 dan 9 jalur, sementara turunan pertama adalah band 11, 10 dan 7 jalur. Model yang dikembangkan menggunakan 11 jalur memperoleh ketepatan 100% (F1), 92% (F2), 95% (F12), 97% ($F1_{dev}$), 90% ($F2_{dev}$) dan 93% ($F12_{dev}$) yang dianggap paling tinggi dalam data tersebut. Selanjutnya, 9 jalur daripada F1 menghasilkan ketepatan yang dapat diterima iaitu 99% dengan nilai Kappa 0.99 ketika menggunakan Pokok halus, Pokok sederhana, Pokok kasar, dan Regresi linear. Walau bagaimanapun, ia memerlukan pra-proses yang kompleks untuk memisahkan F1 dari pelepah lain, yang akan meningkatkan masa pengkomputeran. Oleh itu, 11 jalur daripada F12 dapat memberikan model klasifikasi yang hampir baik dengan ketepatan 95% dan nilai Kappa 0.9 menggunakan mesin vektor sokongan (SVM) linear dan SVM kuadratik. Walaupun begitu, penggunaan F12 dapat mengurangi waktu pra-proses kerana tidak perlu memisahkan antara F1 dan F2. Maklumat ini berguna dalam aplikasi pandangan udara ketika menggunakan kenderaan udara tanpa pemandu (UAV) untuk pemerolehan gambar kerana kedua pelepah dapat dilihat dengan jelas dari gambar pandangan atas sehingga dapat mempercepat pengesanan penyakit BSR.

ACKNOWLEDGEMENTS

With the name of Allah, the Most Compassionate and Most Merciful

All praise and thanks to Almighty Allah, with His blessing giving me the strength and passion in completing my research until this thesis is compiled.

I would like to express my sincere gratitude to my supervisor, Assoc. Prof. Dr. Siti Khairunniza binti Bejo for her continuous support, patience, encouragement, and immense knowledge throughout my research. Her guidance helped me every time I was in trouble or had a question concerning my research and writing.

Besides my supervisor, I would also like to thank the rest of my supervisory committee: Assoc. Prof. Dr. Farrah Melissa binti Muharam, Dr. Mahirah binti Jahari, and Prof. Ian Yule, for their insightful comments, inspiration and the hard questions which incented me to widen my research from various perspectives.

I would also like to thank the assistant engineer, Mr. Ghazali bin Kassim and my fellow labmates for their involvement in my research, stimulating discussions, and the fun we have had in the past two years.

Finally, I would like to thank my family for providing me with unfailing support and continuous motivation throughout my years of study and through the process of researching and writing this thesis. This accomplishment would not have been possible without them.

Thank you.

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

AISA	Airborne imaging spectrometer for application
ANOVA	Analysis of variance
ASW	Average silhouette width
BSR	Basal stem rot
F1	Frond 1
F2	Frond 2
G. boninense	*Ganoderma boninense*
H	Uninoculated seedlings
kNN	k-nearest neighbor
LDA	Linear discriminant analysis
NIR	Near-infrared
OIF	Optimum index factor
PCR	Polymerase chain reaction
QDA	Quadratic discriminant analysis
RWB	Rubber wood block
SPAD	Soil plant analysis development
SVM	Support vector machines
U	Inoculated seedlings
UAV	Unmanned aerial vehicle

CHAPTER 1

INTRODUCTION

1.1 Research background

Oil palm (*Elaeis guineensis*) is a palm species that has been extensively planted in Southeast Asia, primarily in Indonesia and Malaysia, to fulfil the global demand for vegetable oil due to increasing population, income, and growing biofuel market. In Malaysia, oil palm is the main commodity crop that has significantly contributed to the economic development and stability of the country. Furthermore, exports of palm-based products such as palm oil, palm kernel oil, palm kernel cake and palm-based oleochemicals rose by 12.1% to 27.88 million tonnes as compared to the previous year (MPOB, 2019), maintaining Malaysia as the second-largest exporter in the world.

Malaysia falls under the tropical rainforest climate, which is typically hot, rainy, and very humid. The average temperature ranges from 24 to 32°C with an annual rainfall of around 2000 mm, which is favourable for oil palm growth. The land is also biophysically suitable for oil palm cultivation (Pirker and Mosnier, 2015). As a result, the area planted with oil palms in Malaysia continues to grow annually, with the latest total of 5.9 million hectares (MPOB, 2019). These plantations accounted for 32% of the world palm oil production, which denoted 38% of world exports (Breslin and Nesadurai, 2020). Besides climate and land suitability, the development of Malaysia's oil palm industry is also driven by government policies, government-private sector network cooperation, and technology advancement (Rasiah and Shahrin, 2006).

Nevertheless, the production of oil palm in Southeast Asia has been affected by a never-ending basal stem rot (BSR) disease caused by the *Ganoderma boninense* (*G. boninense*) pathogen. The BSR disease once infected only mature trees; however, a recent study by Sanderson (2005) has reported that seedlings are also susceptible to the infection where the symptoms appear earlier and more severe. The disease affects a plantation by reducing the number of standing trees and the weight of fresh fruit bunches (FFB) (Flood et al., 2000). According to Subagio and Foster (2003), the FFB yield decreased by an average of 0.16 t ha^{-1} for every dead palm or 35% when half of the planted trees died. Meanwhile, Malaysia has reported annual losses of up to RM 1.5 billion due to this disease, making BSR the most economically devastating disease. Based on the BSR incident rate, the total area affected in 2020 was estimated to be 443,440 hectares, equivalent to 65.6 million oil palms, which is worrying if preventive measures are not implemented (Roslan and Idris, 2012).

G. boninense is a white-rot fungus that cultivates within oil palm stem through uninjured roots while producing enzymes that could degrade the woody tissues, cellulose, and lignin layers of the stem (Paterson, 2007). It also affects the xylem, causing a major water and nutrient distribution problem to the top part of the tree, making the symptoms appear similar to water stress and nutrient deficiency (Turner and Gillbanks, 1974; Shu'ud et al., 2007; Paterson, 2007). Nutrient deficiency could cause poor production of new leaves resulting in yellowing and browning of older leaves. In severe cases, there is no development of new leaves and fresh bunches, which leads to growth inhibition and yield reduction. According to Idris et al. (2006), *G. boninense* infection could cause 80% of the affected trees to die and 25% to 40% FFB yield losses. However, the trees with an infection of less than 20% can still be treated (Meor et al., 2009). Therefore, it is crucial to detect the BSR disease at an early stage.

The earliest visual symptom of *G. boninense* infection in oil palm seedlings can be seen in the presence of fruiting bodies at the seedling's bole. Meanwhile, the medium symptoms are partial yellowing of leaves or mottling of basal fronds to form necrosis, indicating that over 50% of the stem base has been internally damaged (Naher et al., 2015). However, the fruiting body at the infected bole may present or may not present before or after developing foliar symptoms (Sariah et al., 1994; Idris et al., 2006), making visual identification complicated and confusing. In short, the disease could change the physical appearance and growth of oil palm seedlings, especially in terms of frond count, height, girth, and chlorophyll content of leaves (Naidu et al., 2018). These are all due to the inability to perform normal photosynthesis due to foliar symptoms and water deficiency (Haniff et al., 2005).

Hyperspectral imaging is a passive sensor that measures the light reflected from each pixel of a scene in narrow and contiguous electromagnetic wavelengths. Every pixel in the hyperspectral image contains a complete spectral reflectance equal to the number of wavebands. Such reflection provides enough information to classify and analyse existing materials within the image that makes it possible to detect plant disease remotely (Susič et al., 2018). The recorded spectral reflectance normally represents chlorophyll content, cell structure and water content of leaves (Khosrokhani et al., 2016) that are important for determining plant health status. This device can cover a large-scale plantation in a single flight to collect information faster and thoroughly than the field workers. Shafri et al. (2011) stated that the rationale of using high dimensionality data is to improve the efficacy of discrimination between more specific features and classes.

Some applications of hyperspectral imaging for early identification, rapid evaluation and visualisation were demonstrated by Bravo et al. (2003), Bauriegel et al. (2011), Hillnhütter et al. (2011), Kumar et al. (2012), Calderón et al. (2013), Lowe et al. (2017), Kuska et al. (2015), Moghadam et al. (2017), Xie et al. (2017), Kong et al. (2018) and Bohnenkamp et al. (2019). These researchers used the acquired hyperspectral images and extracted spectral information to study the disease infection in plants. The results generated a high degree of accuracy, which verified the capability of this technique for the early detection of plant disease.

1.2 Problem statement

To date, there is no convenient method has been developed for the early detection of BSR disease. The common practice in plantations is manual detection through visual examination of physical symptoms that are considered as low accuracy, inconsistent result, time-consuming and labour-intensive due to human dependency. Another major downside of manual detection is the lack of standard physical symptoms coupled with error-prone methods, which have led to contradictory assessment (Izzati et al., 2008; Kok et al., 2013; Naidu et al., 2018). In contrast, laboratory-based methods are reliable for early disease detection. However, it is only applicable to small scale samples since it comprises stem collection and tedious laboratory procedures (Naher et al., 2013). Meanwhile, a spectroscopy device can detect an early stage of BSR disease in oil palm seedlings using reflectance spectra of leaves (Shafri and Anuar, 2008; Shafri and Hamdan, 2009; Shafri et al., 2011; Izzuddin et al., 2017). However, this device can only take one reading per time for a tiny leaf area, thus increasing data collection duration and impractical for large scale plantations.

Based on previous studies, it can be concluded that hyperspectral imaging is feasible to be used for early detection of BSR; yet no study has been conducted for oil palm seedlings. Oil palm seedlings at the age of 12 – 48 months old are susceptible to *G. boninense* infection after being transferred and planted in a plantation (Sanderson, 2005). Early detection of infection is crucial to ensure sufficient treatment time, which prevents the disease from spreading. The hyperspectral imaging studies available at this time were carried out in oil palm plantations using vegetation indices and conventional classification methods (Shafri and Hamdan, 2009; Shafri and Mohanad, 2009; Shafri et al., 2012; Izzuddin et al., 2015; Izzuddin et al., 2018). The results obtained by Shafri and Mohanad (2009), Shafri and Hamdan (2009), and Shafri et al. (2012) showed a positive correlation of over 80% between reflectance spectra of leaves and BSR status of oil palm trees. These studies supported the potential use of hyperspectral imaging in collecting spectral information to distinguish between healthy and *G. boninense* infected oil palm seedlings.

1.3 Objectives

The general objective of this research is to detect an early stage of *G. boninense* in oil palm seedlings based on the growth of seedlings, spectral reflectance of leaves and machine learning classification.

The specific objectives of this research are:

1. To examine the effects of *G. boninense* infection on the physical growth of oil palm seedlings.

2. To assess the spectral reflectance of leaves taken from different fronds number at the uninoculated (H) and inoculated (U) condition.

3. To identify the best classification models for early detection of *G. boninense* using machine learning techniques.

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LIST OF PUBLICATIONS

Azmi, A. N., Bejo, S. K., Jahari, M., Muharam, F. M., & Yule, I. (2021). Differences Between Healthy and Ganoderma boninense Infected Oil Palm Seedlings Using Spectral Reflectance of Young Leaf Data. *Basrah Journal of Agricultural Sciences*, *34*, 171-179.

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