UNIVERSITI PUTRA MALAYSIA

INTERNET OF THINGS-BASED SOIL SENSING PLATFORM FOR Ganoderma boninense INFECTION DETECTION IN OIL PALM SEEDLINGS USING MACHINE LEARNING

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

April 2021

DEDICATION

This thesis is dedicated to

My lovely family, wife, and kids:

With love, respect, and a bunch of memories
Indeed, we belong to Allah and indeed to Him we will return.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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Chairman : Associate Professor Siti Khairunniza binti Bejo, PhD
Faculty : Engineering

Basal stem rot (BSR), caused by a white-rot fungus *Ganoderma boninense* is a destructive disease that causes tremendous losses in the oil palm industry. The primary route of the disease infection is through root that has contact with *Ganoderma boninense* inoculum in the soil. The use of planting materials (seedlings) that are resistant to *Ganoderma boninense* could prevent the spread of BSR disease in the plantation. A manual census is used commonly by nurseries to monitor the progress of the disease development associated with various treatments. This common nursery practice is usually conducted every two to four weeks. An irregular monitoring leads to delays in detecting the disease occurrence. This study, therefore, is focused on the use of a sensor network to obtain soil data to diagnose the *Ganoderma boninense* infection using the internet of things (IoT) platform. This approach could lead to a possible early infection detection methodology since rapid monitoring can avoid missing data. The objectives of the research include studying the potential use of soil properties as the indicators for BSR disease, analyzing temporal changes of infected seedlings, and developing the *Ganoderma boninense* disease detection model using soil properties. A total of 40 oil palm seedlings aged five months old were used in the study. They consisted of 20 healthy and 20 infected seedlings. The infected seedlings were prepared by artificially inoculating the tree roots with *the Ganoderma boninense* rubber woodblock. The seedlings were placed in the greenhouse with controlled environmental temperature and humidity. Three soil sensors were buried at 8 cm depth in each seedling's growth medium to measure the amount of soil moisture content (MC) in volumetric water content (in %), soil electrical conductivity (EC) (in µS/cm), and soil temperature (T) (in °C). The soil parameters data was collected every hour daily for 24 weeks (six months). These data were stored in the cloud (ThingSpeak) and available for real-time monitoring and data extraction for further analysis. The results of soil analysis revealed that more than 80% of monitored weeks in all parameters yielded significant differences (P-value < 0.05) between healthy and infected seedlings when tested using a t-test at 5% significance level. Detail analysis was later conducted to check on how soon these changes can be observed by analyzing its temporal data based on a daily, weekly, and monthly basis. The temporal data collected showed the same fluctuation pattern of healthy and infected seedlings, however, among all the parameters, only EC responded to the fertilizer application activities in both categories. In general, based on the daily and weekly monitoring basis, the values of MC, EC, and T for healthy seedlings are higher than infected seedlings in the whole 24 weeks and the first 15 weeks, respectively. For the monthly monitoring basis, the values of MC and EC gave the same trend, while the values of T for infected seedlings were higher than healthy seedlings in the last two months of the six months monitoring period. Detection models were developed using seven classifiers of machine learning algorithms. The optimization process was conducted by analyzing the possibility of reducing the number of soil parameters and reducing the number of temporal data. In general, the results showed that the use of all soil parameters performed better in all weeks compared to the reduced soil parameters and PC data. The results also showed that the model with 6 hours of input data collected every three days at 2 – 7 am gave the most accurate results with an average accuracy of 98.3%. The Fine k-Nearest Neighbors (Fine kNN) algorithm was identified as the best classifier to differentiate between healthy and infected seedlings. Among 414 models developed using reduced data, 269 (65%) of the models with the highest accuracy obtained using Fine kNN. It can be concluded that the major contribution of the study is on the development of the machine learning model suitable for detection of *Ganoderma boninense* infection in an oil palm seedling as early as 12^{th} weeks after infection using the rapid soil sensing data through the IoT platform. The proposed method, hopefully, can help in better management of the disease and thus, increase the oil palm yield.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PLATFORM PENGINDERAAN TANAH BERDASARKAN INTERNET PELBAGAI BENDA UNTUK PENGESANAN JANGKITAN *Ganoderma boninense* DI DALAM ANAK POKOK KELAPA SAWIT MENGGUNAKAN PEMBELAJARAN MESIN

Oleh

MOHD HAMIM BIN ABDUL AZIZ

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Reput pangkal batang (RPB) yang disebabkan oleh kulat reput putih *Ganoderma boninense* adalah penyakit yang merosakkan yang menyebabkan kerugian besar dalam industri kelapa sawit. Laluan utama jangkitan penyakit ini adalah melalui akar yang mempunyai sentuhan dengan inokulum *Ganoderma boninense* di dalam tanah. Penggunaan bahan tanaman (anak pokok) yang rintang terhadap *Ganoderma boninense* mampu mengekang penularan RPB di dalam ladang. Bancian secara manual biasanya dipraktikkan di tapak semaian untuk memantau perkembangan pembentukan penyakit yang terkait dengan pelbagai rawatan. Amalan bancian di tapak semaian ini kebiasaannya dilakukan setiap dua ke empat minggu. Pemantauan yang tidak berkala membawa kepada kelewatan dalam mengesan kejadian penyakit. Oleh itu, kajian ini berfokus kepada penggunaan jaringan penderia bagi mendapatkan data tanah untuk mendiagnos jangkitan *Ganoderma boninense* menggunakan platform internet pelbagai benda (IPB). Pendekatan ini memungkinkan kaedah pengesanan awal jangkitan kerana pemantauan secara pantas dapat mengelakkan kehilangan data. Objektif-objektif kajian termasuk untuk mengkaji potensi penggunaan sifat tanah sebagai petunjuk penyakit RPB, untuk menganalisis perubahan berkala yang berlaku pada pokok yang telah dijangkiti dan untuk membina model pengesanan penyakit menggunakan sifat-sifat tanah. Sebanyak 40 anak pokok yang berusia lima bulan digunakan dalam kajian. Ianya terdiri daripada 20 anak pokok sihat dan 20 anak pokok yang dijangkiti. Teknik inokulasi buatan digunakan bagi menyediakan sampel anak pokok yang dijangkiti. Teknik ini dilakukan dengan melekatkan akar anak pokok dengan blok kayu getah *Ganoderma boninense*. Anak pokok tersebut diletakkan di dalam rumah hijau yang dikawal suhu dan kelembapan persekitarannya. Tiga penderia tanah diletakkan dalam medium pertumbuhan anak pokok sawit pada kedalaman 8 cm untuk mengukur jumlah kandungan kelembapan (KK) tanah dalam unit isipadu

kandungan air (dalam %), konduktiviti elektrik (KE) tanah (dalam µS/cm), dan suhu (S) tanah (dalam °C). Pengambilan data tanah dilakukan setiap jam setiap hari selama 24 minggu (6 bulan). Data-data ini disimpan di dalam awan (ThingSpeak) dan sedia ada untuk pemantauan waktu sebenar dan pengekstrakan data bagi tujuan analisis lanjut. Keputusan analisis tanah telah menunjukkan bahawa lebih 80% daripada minggu pemantauan dalam semua parameter telah memberikan perbezaan yang signifikan (nilai-P < 0.05) antara anak pokok yang sihat dan yang dijangkiti apabila diuji dengan menggunakan ujian-t pada tahap signifikan 5%. Analisis lanjut kemudiannya dilakukan untuk mengesan bilakah perubahan ini boleh dilihat dengan menganalisis data berkala secara harian, mingguan dan bulanan. Walaupun anak pokok yang sihat dan yang dijangkiti memberikan pola turun-naik yang sama, namun, antara kesemua parameter, hanya KE yang memberikan maklumbalas terhadap aktiviti pembajaan dalam kedua-dua kelas. Secara umumnya, berdasarkan kepada pemantauan secara harian dan mingguan, nilai KT dan KE; dan S untuk anak pokok sihat adalah lebih tinggi berbanding anak pokok yang dijangkiti masing-masing disepanjang 24 minggu dan 15 minggu yang pertama. Bagi pemantauan secara bulanan, Nilai KK dan KE memberikan pola yang sama, manakala nilai S bagi pokok yang dijangkiti adalah lebih tinggi pada dua bulan yang terakhir daripada enam bulan pemantauan. Model pengesanan telah dibangunkan dengan menggunakan tujuh algoritma pengelasan Pembelajaran Mesin. Proses pengoptimuman telah dilakukan dengan mengurangkan bilangan parameter dan mengurangkan bilangan data berkala. Secara umumnya, keputusan menunjukkan bahawa penggunaan semua parameter tanah memberikan keputusan yang lebih baik dalam semua minggu dibandingkan dengan parameter tanah yang dikurangkan dan data KP. Keputusan juga menunjukkan model yang dibina dengan input data 6 jam yang diambil setiap hari tiga hari pada pukul 2 - 7 pagi telah memberikan keputusan yang paling tepat dengan purata ketepatan adalah 98.3%. Model k-Jiran-jiran Terdekat halus (kJD halus) dikenalpasti sebagai pengelas terbaik untuk membezakan antara anak pokok sihat dan anak pokok sakit. Antara 414 model-model yang dibina menggunakan data yang dikurangkan, 269 (65%) daripada model-model tersebut diperolehi dengan menggunakan kJD halus. Ianya dapat disimpulkan bahawa sumbangan utama kajian adalah pada pembangunan model pembelajaran mesin yang sesuai untuk pengesanan jangkitan *Ganoderma boninense* pada anak pokok sawit seawal 12 minggu selepas jangkitan menggunakan penderian tanah yang pantas melalui platform IPB. Kaedah yang dicadangkan diharap dapat membantu dalam pengurusan penyakit yang lebih baik seterusnya mampu meningkatkan hasil kelapa sawit.

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Date: 12 August 2021

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LIST OF ABBREVIATIONS

AISA	Airborne Imaging Spectrometer for Applications
ANOVA	Analysis of Variance
ARVI	Atmospherically Resistant Vegetation Index
BSR	Basal Stem Rot
CRI	Continuum Removal Indices
CS	continuous significant hours
CV	coefficient of variation
D	Discriminant
DA	Discriminant Analysis
DOSM	Department of Statistic Malaysia
DT	Decision Tree
E	Ensemble
EC	electrical conductivity
EDTA	ethylenediaminetetraacetic acid
EH	even hours
ELISA	Enzyme-linked immunosorbent assay
ENVI	Environment for Visualizing Images
GBNDVI	Green Blue Normalized Difference Vegetation Index
GDP	Gross Domestic Product
GRWB	*Ganoderma* rubber wood block
HS	healthy seedling
IoT	Internet of Things
IS	infected seedling

ITAFoS	Institute of Tropical Agriculture and Food Security
KNB	Kernel Naïve Bayes
kNN	k-Nearest Neighbors
LDA	Linear Discriminant Analysis
MC	moisture content
MPOC	Malaysian Palm Oil Council
MS	most significant hours
NB	Naïve Bayes
NDVI	Normalized Difference Vegetation Index
NN	Neural Networks
NPK	Nitrogen, Phosphorous, K for Potassium
PABs	polyclonal antibodies
PC	principal component
PCA	principal component analysis
PCR	Polymerase chain reaction
PLSR	Partial Least Square Regression
QDA	Quadratic Discriminant Analysis
r	correlation coefficient
R^2	coefficient of determination
RCBD	Randomized Complete Block Design
RF	Random Forest
RWB	rubber wood block without *Ganoderma*
SD	standard deviation
SVM	Support Vector Machine
T	temperature

TEM	Transmission Electron Microscopy
UART	Universal Asynchronous Receiver/Transmitter
UPM	Universiti Putra Malaysia
USA	United States of America
V_{air}	volume of air
V_{soil}	volume of soil
V_{water}	volume of water
VWC	volumetric water content

CHAPTER 1

INTRODUCTION

1.1 Research background

Oil palm (*Elaeis guineensis*) is the most planted commodity crop in Malaysia that yielded millions of tons of crude palm oil per year. Malaysia is the second-largest palm oil producer and exporter in the world (after Indonesia), with approximately 18 million tons exported per year. The United States, the European Union, China, India, and Pakistan are among the major importers of Malaysian palm oil (May, 2012).

The oil palm production in Malaysia is threatened by Basal Stem Rot (BSR) disease caused by the wood-rotting fungus named *Ganoderma boninense,* which reduces oil palm production (Idris et al., 2000). According to Chong et al. (2017), yearly losses in Malaysia due to this disease can be up to RM 1.5 billion. The disease is considered to be the biggest threat to the palm oil industry in Malaysia (Idris et al., 2000).

Infected oil palm trees mostly recognizable by visual inspection on the trees' foliar, stem, and trunk i.e., the presence of unopened spear leaves, yellowish fronds, fronds hanging downward, small canopy size, rot at the basal part of the stem, and the existence of fruiting bodies on the trunks (Gurmit, 1991; Ariffin et al., 2000; Kandan et al., 2010). The infection causes damage to the internal tissue of trees, which consequently disrupts the water and nutrient uptake to the trees (Rees et al., 2009). It could also affect the ability of the trees to perform normal photosynthesis due to water deficiencies and foliar symptoms (Haniff et al., 2005).

The disease can attack oil palm trees at nurseries and plantations. *Ganoderma boninense* is a soil-borne fungus that survived in the soil before invading its host. The primary route of infection appears to be through root contact with inoculum sources in the soil (Rees et al. 2009). It was proven through studies in oil palm seedling. The infection of the disease in oil palm seedlings through root contact with *Ganoderma* inoculum was also confirmed by Alexander et al. (2017). High incidences of infection were recorded in locales where many old oil palm trees were felled and the stumps left to rot on the ground. Thus, creating a friendly environment for fungi to grow on a wounded host in the soil. Subsequently, the disease spreads from a plant to another either by roots or spores (Paterson, 2007). When the fungi invaded the roots (Rees et al, 2009), it damaged the structure of the roots (Alexander et al., 2017) and as a result disturbed the operational function of water and nutrient uptake by roots (Fitter, 1991).

Generally, the survival of a soil-borne fungal is significantly related to soil moisture content (Eastburn and Butler, 1991; Garret, 1938; Gill et al., 2001; Chang, 2003), nutrient content (Yadav et al., 2011; Rashid et al., 2016) and temperature (Nawawi and Ho, 1990; Saremi and Burgess, 2000; Rees et al., 2007), either directly or indirectly (Liddell, 1992). The high moisture content of coastal soils invigorates *Ganoderma boninense* to grow (Gurmit, 1991). The BSR disease favors soils with poor drainage and high water retention capacity. However, this report contradicted the report by Chang (2003) that suggested flooding the infected area as a way to control the spread of the disease. This is based on the notion that the high soil moisture content makes it harder for *Ganoderma boninense* to survive. This condition was tested based on laboratory conditions. Therefore, we can conclude that perhaps there exists a certain range of soil moisture content that favors the occurrence of *Ganoderma boninense* disease, but not due to a high or low value of soil moisture content. Under laboratory conditions, Nawawi and Ho (1990) reported that *Ganoderma boninense* were found to grow at an optimum soil temperature between 27-30°C. Gurmit (1991) reported that high salinity appeared to suppress the disease's spread. Soil electrical is a measure of the amount of salt in the soil. It is an important indicator of soil health.

The proliferation of internet usages in the wide spectrum of industries and the innovation of the Internet of Things or IoT have also positively impacted agriculture practices. A wide range of applications was developed to assist the agricultural industry and amongst them is plant disease detection and prediction. Foughali et al. (2018) used the IoT platform to monitor the environmental temperature and humidity to predict the potential attack of the fungal infection in potatoes. Based on the environmental data, the risk of the disease occurrence was measured and predicted by a parameter called "Blight units". When the defined threshold of Blight units reached favorable values for the disease occurrence i.e., humidity > 90% for a day and average temperature at 15 – 21 °C, the system notifies the farmers via SMS to begin treatment. A similar approach was adopted by Patil and Thorat (2016), Truong et al. (2017), and Materne and Inoue (2018) to predict the occurrence of disease due to fungal attacks in various types of plants. While Sarangdhar and Pawar (2017), Nandhini et al. (2018), Mathana and Nagarajan (2020), Pan and Wang (2021), Sowmyalakshmi1 et al. (2021), and Devi et al. (2021) used IoT platform and images to detect the disease occurrence in various types of plants. As a conclusion, along with the environmental conditions and/or leaves images monitoring, some research deployed soil sensors to measure soil moisture content, electrical conductivity, and temperature as additional data.

1.2 Problem statement

The impact of diseases in plants can be reduced through proper management of cultural practices, agronomic, and phytosanitary. However, it should be implemented with the use of planting materials (seedlings) which are resistant to *Ganoderma boninense* (Turnbull et al., 2014) to prevent the spread of BSR disease in the plantation and eventually economic losses (Idris, 2009; Turnbull et al., 2014). A comprehensive study to determine the level of resistance or susceptibility of the planting materials to disease is an important aspect to be looked at before any development of a successful breeding program and for the sustainability of this crop, particularly in Southeast Asia (Breton et al., 2009). Breeding programs to develop planting materials resistant to *Ganoderma boninense* involves long-term studies if it only involves field trials. This is because the environmental conditions and other extraneous variables in the field are much difficult to control than the glasshouse or nursery due to the spatial variability in the field. These uncontrollable environmental conditions can affect the optimum growth of the plants (Rebitanim et al., 2020). Distinguishing plants' different levels of susceptibility and resistance to the disease is of utmost importance hence, it is crucial to conduct an artificial inoculation of the pathogen at the nursery level to create an early screening test (Breton et al., 2009).

In common nursery practices, a manual census used to monitor the progress of the disease development associated with various treatments (Parker et al., 2007; Chung, 2012) was done by a human. It is normally conducted every two to four weeks. This irregular monitoring leads to delays in detecting the disease occurrence. Furthermore, human inspection relied heavily on the visible symptoms of the disease. It is prone to error due to a lack of experience and subjective judgements. Laboratory-based methods provide high accuracy of detection, however, it is time-consuming, complicated, labour intensive, and costly (Naher et al., 2013). Researchers had proposed various types of remote sensing approaches with different levels of detection accuracies. However, none of them provide a regular and rapid monitoring approach which can cause delays in detecting the disease occurrence.

Based on the literature, there is conclusive evidence that regular and rapid monitoring of disease development in a plant using an IoT platform could lead to early detection as possible missing of useful data could be avoided. The approach used in this study shows the potential use of rapid monitoring for soil-borne disease detection due to *Ganoderma boninense* infection. Furthermore, an intensive study can be performed to understand the *Ganoderma boninense* infection in oil palm seedlings associated with soil properties.

1.3 Objectives

The general objective of this thesis is to study the capability of a soil sensing network to detect the changes of the soil properties due to the *Ganoderma boninense* infection in oil palm seedlings. The specific objectives of this thesis are:

1. To determine the relationships between soil moisture content, soil electrical conductivity, and soil temperature in oil palm seedlings.
2. To identify the optimum interval of monitoring time for BSR disease detection by analysing temporal changes of soil moisture content, soil electrical conductivity, and soil temperature in relation to *Ganoderma boninense* infection.
3. To develop a model for *Ganoderma boninense* infection detection using an optimal dataset and machine learning approach.

1.4 Scope and limitation

The study was conducted at a transgenic greenhouse under the management of the Institute of Tropical Agriculture and Food Security (ITAFoS), Universiti Putra Malaysia. The seedlings were grown in a greenhouse under controlled environmental temperature and humidity. A suitable environmental temperature and humidity are important for the optimum growth of the seedlings in the greenhouse. It is difficult to control the environmental condition if the seedlings are grown in an open area in the plantation or estate. Oil palm seedlings used in this study are from the *tenera (dura x pisifera)* variety. A drip irrigation system was used to supply water to the seedlings. A fertilizer with NPK ratio of 15:15:15 was used to grow the seedlings. Soil properties parameters measured in this study were soil moisture content measured as a percentage of volumetric water content (%), soil temperature (^{0}C) and, salinity measured as electrical conductivity in units of micro Siemens per centimetre (µS/cm). The monitoring period was six months or 24 weeks. The eminence penetration or invasion of *Ganoderma boninense* into the roots or bowl system of the seedlings was verified through laboratory analysis using the PCR (Polymerase chain reaction) method by taking two random samples of seedlings after two months of inoculation. If the PCR test analysis on all inoculated seedlings shows positive results then those seedlings were assumed to be infected by *Ganoderma boninense* inoculum.

1.5 Structure of the thesis

Chapter 2 presents a literature review that covers topics like oil palm growth, economic value, BSR disease that affects the production of the oil palm, soil properties associated with the soil-borne fungi growth and control, and the available methods used for the disease detection. The application of the Internet of Things in agriculture and a review on temporal monitoring applied in oil palm seedling for monitoring the artificial inoculation progress was also described. This chapter also covers a review of the technique of the machine learning application employed for BSR and other various diseases in agriculture.

Chapter 3 presents a proposed method used for the *Ganoderma boninense* disease detection in oil palm seedlings. The chapter gives a brief overview of the study area and the facilities available in the greenhouse. It is followed by a brief explanation of the method of inoculating artificial *Ganoderma boninense* to the plants and the experimental design of the fieldwork. A standard lab-based method used to confirm the infection of the *Ganoderma boninense* is discussed. Then this chapter gives a detailed explanation of the system sets up – a sensing network used to collect data and store it in the cloud for online monitoring. It includes hardware and software integration to develop the system. Statistical analysis then used to find the relationship between each parameter and pattern of its temporal changes over time were also presented. Finally, it presented the technique of machine learning used to classify the seedlings.

Chapter 4 presents the results and discusses the findings of the study. The result of the study presents the significance of soil properties to be used to detect the *Ganoderma boninense* infection. This chapter also cites the results of soil properties' relationship with each other concerning the *Ganoderma boninense* infection. Then, the chapter divulges details of temporal analysis of the soil parameters reading in monthly, weekly, daily, and hourly. Results of the multi-temporal analysis were then used to select the more significant data as input data for the classification model development. The last subtopic in this chapter analysed and discussed the development of the classification model using machine learning. The models developed using different types and selection of data were compared to get the best model.

Finally, the conclusions of the study were presented in Chapter 5. This chapter describes the main contributions of the study and some suggestions on the future work to be undertaken.

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