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EARLY DETECTION OF ORANGE SPOTTING DISEASE IN OIL PALM USING RED EDGE PARAMETERS

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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

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DEDICATION

Dedicated to Lord Sri Venkatesha"

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

EARLY DETECTION OF ORANGE SPOTTING DISEASE IN OIL PALM USING RED EDGE PARAMETERS

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July 2018

Chairman : Associate Professor Siva Kumar Balasundram, PhD
Faculty : Agriculture

Viroids are single-stranded, low molecular weight, circular RNA between 246 and 401 nucleotides that lacks a protective protein coat. Viroids have only been found in the plants. Coconut cadang-cadang viroid (CCCVd; Genus Cocadviroid, Family Pospiviroidae) is one of the known species of viroids that has been reported to cause Orange Spotting (OS) disease in the oil palm (*Elaeis guineensis* Jacq.; Arecaceae). OS disease is an emerging oil palm disease in Malaysia. Variants of CCCVd have been reported in both symptomatic and asymptomatic oil palm. Currently, there is no direct control measure reported that can be recommended to control OS disease. Replacement of the infected plants is the only measure to reduce losses. Molecular marker techniques are used to detect CCCVd-infected plants. But these techniques are destructive and typically take a longer time in molecular analysis and sequence characterisation. Therefore, for early disease detection, visible-near infrared spectroscopy was employed for the first time at the leaf scale to screen oil palm seedlings using a hand-held spectroradiometer. Glasshouse experiment was conducted on three-month-old inoculated and healthy oil palm seedlings for a duration of four months in two different years, 2015 and 2017. In this research, oil palm seedlings were inoculated with a CCCVd oil palm variant (OP246), and an ASD spectroradiometer was employed to measure reflectance from inoculated and control seedling. In particular, the red edge region (680-780 nm), which has been frequently shown to indicate plant stress, was investigated for selection of red edge wavebands, red edge indices, and development of the Orange Spotting Disease Index (OSDI) using red edge parameters. Firstly, using a standard foreoptic with a 25° Field of View (FOV), two red edge wavebands (i.e. 680 nm and 754 nm) were identified. Their reflectance sensitivity was also examined. Secondly, using a contact probe, two other red edge wavebands (i.e., 700 nm and 768 nm) and a red edge index (i.e., Enhanced Vegetation Index 2) were identified. Finally, a simple ratio, i.e. the sum of the first derivative spectra of right side – Red Edge Point (REP) to the sum of the first derivative spectra

of left side – REP of the red edge region, was developed as an OSDI. The OSDI values between experiment batch of 2015 and 2017 demonstrated a strong correlation (r = 0.96). The OSDI is a first spectral index developed for early detection of OS disease at the leaf scale and can be tested at canopy scale in the future. This study has proved that OS disease can be detected at an early stage using a hand-held spectroradiometer.

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

PENGESANAN AWAL PENYAKIT TOMPOK JINGGA DI KELAPA SAWIT MENGGUNAKAN PARAMETER KELEBIHAN MERAH

Oleh

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Viroid adalah organisma yang sangat kecil mengadungi satu rantai, berat molekul yang rendah, size RNA diantara 246 dan 401 nukleotida dan tidak mempunyai lapisan protein pelindung. Viroid hanya ditemui di tumbuh-tumbuhan. Coconut cadang-cadang viroid (CCCVd; Genus *Cocadviroid*, Family Pospiviroidae) adalah salah satu spesies viroid yang diketahui yang menyebabkan Penyakit Orange Spotting (OS) dalam kelapa sawit (*Elaeis guineensis Jacq., Arecaceae*). Penyakit OS dalam kelapa sawit adalah penemuan terbaru di Malaysia. Varian CCCVd telah dilaporkan dalam kedua-dua kelapa sawit simtomatik dan asimptomatik. Pada masa ini, tiada langkah kawalan langsung yang dilaporkan yang boleh disyorkan untuk mengawal penyakit OS. Penggantian tumbuhan yang dijangkiti hanyalah langkah untuk mengurangkan kerugian. Teknik molekul digunakan untuk mengesan tumbuhan yang dijangkiti CCCVd. Tetapi teknik ini merosakkan dan biasanya mengambil masa yang lebih lama dalam analisis molekul dan jujukan rantai DNA. Oleh itu, untuk pengesanan penyakit awal, spektroskopi inframerah yang kelihatan pada masa dahulu digunakan pada skala daun untuk menanam benih kelapa sawit menggunakan spectroradiometer tangan. Dalam kajian ini, biji benih kelapa sawit disuntik dengan varian kelapa sawit CCCVd (OP_{246}) dan spectroradiometer ASD digunakan untuk mengukur anak benih yang disuntik. Anak kelapa sawit diletak di kaca rumah dilakukan selama lebih dari tiga bulan dalam dua tahun yang berlainan, iaitu tahun 2015 dan 2017. Khususnya, kawasan gelombang merah (680-780 nm), yang sering ditunjukkan untuk menunjukkan tekanan tumbuhan, disiasat diikuti oleh pemilihan pada kawasan tepi gelombang merah, indeks kelebihan merah, dan perkembangan Indeks Penyakit Bercahaya Orange (OSDI) dengan menggunakan parameter tepi merah. Pertama, menggunakan 25º foreoptic, dua helai kelebihan merah (iaitu 680 nm dan 754 nm) telah dikenal pasti berdasarkan titik permulaan dan titik cerun curam, masing-masing. Kepekaan and kejituan juga diperiksa. Kedua, menggunakan penyelidikan tumbuhan, dua helai pinggir merah lain (iaitu, 700 nm dan 768 nm) dan indeks kelebihan merah (iaitu, Indeks Peningkatan Tanaman 2) telah dikenalpasti. Nisbah mudah, iaitu jumlah

spektra derivatif pertama sebelah kanan Red Edge Point (REP) kepada jumlah spektra derivatif pertama sebelah kiri - REP dari kawasan pinggir gelombang merah, telah dicatatkan sebagai OSDI. Nilai OSDI antara kumpulan percubaan pada tahun 2015 dan 2017 telah menunjukkan korelasi yang kuat (r = 0.96). OSDI adalah indeks spektrum pertama yang dicatatkan untuk pengesanan awal penyakit OS pada skala daun dan boleh diuji pada skala kanopi pada masa akan datang. Kajian ini telah membuktikan bahawa penyakit OS dapat dikesan pada peringkat awal menggunakan spectroradiometer tangan.

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

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LIST OF ABBREVIATIONS

ANN	Artificial Neural Network
ANOVA	Analysis of Variance
ANS	Automated Network Search
ARS	Agriculture Research Service
ASD	Analytical Spectral Devices
BPNN	Back-Propagation Neural Network
CCCVd	Coconut cadang-cadang viroid
CI	Confidence Interval
CIRE	Chlorophyll Index Red Edge
CChMVd	Chrysanthemum chlorotic mottle viroid
CLSI	Cercospora Leaf Spot- Index
CNN	Convolutional Neural Network
Dai	Days after inoculation
DSWI	Disease –Water Stress Index
ELM	Extreme Learning Machine
EVI 2	Enhanced Vegetation Index 2
FAPAR	Fraction of Absorbed Photosynthetically Active Radiation
FDR	First Derivative of Reflectance
FAO	Food and Agriculture Organization
FOV	Field-of-View
GIS	Geographic Information Systems
GOS	Genetic Orange Spotting
GPS	Global Positioning Systems
GVF	Green Vegetation Fraction

HD	High Definition
HI	Healthy Index
ICTV	International Committee on Taxonomy of Viruses
IR/R	Infrared/Red
LAI	Leaf Area Index
LDA	Linear Discriminant Analysis
LRDSI	Leaf Rust Disease Severity Index
LS-SVM	Least Squares Support Vector Machine
Lw	Laurel wilt
MLP	Multi-Layer Perceptron
MLPNN	Multi-Layer Perceptron Neural Network
MPOB	Malaysian Palm Oil Board
MSA	Multivariate Statistical Analysis
NCBI	National Center for Biotechnology Information
NDVI	Normalized Difference Vegetation Index
NETME	Natrium Chloride EDTA Tris-HCL Mercaptoethanol
NIR	Near Infrared
NLRHI	Normalized Leaf Rust Healthy Index
NN	Neural Network
NPP	Net Primary Productivity
OS	Orange Spotting
OSDI	Orange Spotting Disease Index
PAGE	Poly-acrylamide gel electrophoresis
PAR	Photosynthetically Active Radiation
PC	Principal Component

PC	Peach Calico
PCA	Principal Component Analysis
PCR	Polymerase Chain Reaction
PLS	Partial Least Squares
PMI	Powdery Mildew- Index
PNN	Probabilistic Neural Network
PLMVd	Peach latent mosaic viroid
RBF	Radial-Basis Function
RD	Reflectance Difference
REIP	Red Edge Infection Point
RENDVI	Red Edge Normalized Difference Vegetation Index
REP	Red Edge Point
RF	Random Forest
RNA	Ribonucleic Acids
RPA	Ribonuclease Protection Assay
RS	Reflectance Sensitivity
RT-PCR	The Reverse Transcription-Polymerase Chain Reaction
RT-LAMP	Reverse Transcription Loop-mediated Isothermal Amplification
RVI	Ration Vegetation Index
RWC	Relative Water Content
SAIL	Scattering by Arbitrarily Inclined Leaves
SAVI	Soil Adjusted Vegetation Index
SBRI	Sugar Beet Rust-Index
SD	Shifting Distance
SDI	Spectral Disease Index

SE	South East
SE	Standard Error
SLP	Single-Layer Perceptron
SOM	Self-Organising Map
SR	Simple Ratio
SRI	Simple Ratio Index
SVI	Spectral Vegetation Index
SVM	Support Vector Machine
SWIR	Short-Wave Infrared
TMV	Tobacco Mosaic Virus
UPM	Universiti Putra Malaysia
USDA, FAS	United States Department of Agriculture, Foreign Agriculture Service
VI	Vegetation Index
VNIR	Visible/Near-infrared

CHAPTER I

INTRODUCTION

Oil palm industry is the backbone of Malaysian economy. Malaysia is one of the largest producers and exporters of oil palm in the world. In 2017, Malaysia contributed greatly to the world palm oil industry accounting for approximately 29% of the production and 37% of the exports. In 2017 alone, the total exports of oil palm products has been increased from 23.29 million tonnes to 23.97 million tonnes, which is 2.9% higher than that of 2016 (MPOB, 2018). In the recent years, the Malaysian oil palm industry has been facing significant constraints from crop disease outbreaks leading to significant yield decline.

Orange Spotting (OS) is an emerging disease of oil palm (*Elaeis guineensis* Jacq.; Arecaceae) which has been associated with Coconut cadang-cadang viroid (CCCVd; Genus, *Cocadviroid*, Family, *Pospiviroidae*). Over 40 million coconut palms have been killed by CCCVd since first being described 1914 (Hanold and Randles, 1991a, Randles and Rodriguez, 2003). CCCVd variants characterised from oil palm (i.e. OP_{246}, OP_{297}, OP_{293}, and OP_{270}) had more than 90% sequence similarity with a 296-nt form of CCCVd variant in coconut palm (Vadamalai et al., 2006; Wu et al., 2013). Detection of CCCVd based on molecular biology techniques are destructive, expensive and time consuming. Instead, non-imaging hyperspectral remote sensing is a new indirect diagnostic approach that provides a rapid and non-destructive means to investigate crop disease (Sankaran et al., 2010).

1.1 Background

Recently, non-imaging hyperspectral remote sensing has emerged as a powerful technique for diagnosing a wide range of plant diseases. Non-imaging hyperspectral data are basically multivariate in nature, combining more than hundred contiguous spectral wavebands within the electromagnetic spectrum. Particularly, there has been an ongoing interest in non-imaging Visible/Near-infrared (VNIR) spectroscopy. VNIR spectroscopy employs wavebands between visible and Near-infrared (NIR) range (400-1050 nm) of the spectrum. This is a fast emerging technique that provides an optical means for non-destructive and cost-effective crop diagnosis.

A spectral index that is developed from a ratio of disease sensitive wavebands is called Spectral Disease Index (SDI). This technique involves selection of inflection points (i.e. peaks and troughs) which are found to be sensitive to plant disease. A disease sensitive waveband can indicate crop stress caused by a disease. No study has previously reported on the use of VNIR spectroscopy to diagnose OS disease at the leaf scale (nursery stage). This study aimed at developing Orange Spotting Disease Index (OSDI), which would become the first SDI for OS disease. For this, twenty novel red edge parameters (Li et al., 2016, Liu et al., 2007) were derived from red edge region (680-780 nm) of the electromagnetic spectrum and tested. The red edge region, which is located between the far red and NIR range of the spectrum, has been frequently shown to indicate plant stress.

1.2 Research problems

1. Infection of CCCVd variants which causes bright orange non-necrotic spots (size about 2-3 mm) in oil palm frond, has been reported in commercial plantations in South East (SE) Asia and South West Pacific region (Randles et al., 1980; Imperical et al., 1985; Hanold and Randles, 1991b). Evidence of horizontal and vertical spread of CCCVd in commercial plantations has been seen in recent years. Viroids detected in DxP hybrids in Oceania and SE Asia has revealed a close association between CCCVd and a specific type of OS in oil palm. In addition, commercial oil palm with OS symptoms was reported to show stunting over a period of 5-15 years. OS disease was found to be irreversible and very lethal during this period (Randles et al., 2009).
2. In recent years, for detecting CCCVd in oil palm, many diagnostic assays have been evaluated such as the Reverse Transcription-polymerase Chain Reaction (RT-PCR) (Wu et al., 2013; Vadamalai et al., 2006), Ribonuclease Protection Assay (RPA) (Vadamalai et al., 2009), and Reverse Transcription Loop-mediated Isothermal Amplification (RT-LAMP) (Thanarajoo et al., 2014). These techniques have confirmed presence of low concentration of CCCVd varaints in oil plam. However, due to low concentration of CCCVd, these techniques are neither consistent nor sensitive and not able to quantify the viroid concentrations (Thanarajoo, 2014).
3. Symptom expression is not a necessary outcome of CCCVd infection. Previously reported CCCVd oil palm variants, OP_{297}, OP_{293} and OP_{270}, were all obtained from an asymptomatic oil palm in Malaysia (Vadamalai et al., 2006). In a recent investigation, an oil palm variant ($CCCVd_{293\ OP}$) showed low accumulation of viroid load with no symptoms one year after inoculation (Thanarajoo, 2014).

1.3 Problem Statement

OS disease has similar foliar symptoms to that of potassium deficiency in oil palm. Symtomatic separability between OS disease and potassium deficiency is very difficult to achieve via visual assessment (Selvaraja et al., 2013). Asymptomatic infection of CCCVd even makes detection process much harder. So far, real-time and on the spot detection of OS disease has not been possible using any molecular techniques. To resolve this problem, oil palm seedlings can be screened using a non-imaging hand-held spectroradiometer. The spectroradiometer measures solar radiation reflected from the plants. On the basis of percentage reflectance, healthy and diseased plants can be differentiated. In this research, reflectance of OS infected seedlings will be measured using a spectroradiometer, pre-processed by pre-processing techniques, and analysed by multivariate analyses.

1.4 Scope and relevance

Application of hyperspectral ground sensor (hand-held spectroradiometer) for plant disease diagnosis is gaining much prominence due to its non-destructive feature. To date, there has only been one recent documentation on the use of spectroradiometer for detection of OS disease by Selvaraja et al. (2013) at the canopy scale. They used a spectroradiometer to discriminate between reflectance spectra of OS disease and potassium deficiency, both of which manifest symptoms that are similar.

A hand-held spectroradiometer can be used to screen oil palm seedlings prior to confirmation by any molecular techniques. On the basis of spectral signatures and OSDI values, oil palm seedlings can be differentiated between infected and healthy seedlings. This technique can also be considered as a promising tool for mechanical control of OS disease in order to eliminate infected seedlings. Randles et al. (2009) reported that CCCVd spreads naturally by unknown means. Its eradication has not yet been successful. Currently, it can only be managed by physical removal of affected palms.

The use of spectral signatures and OSDI to detect infected oil palm seedlings is a plausible idea. Mahlein et al. (2012a) studied different spectral signatures on host-pathogen (sugar beet-fungi) interaction for early detection of fungal leaf diseases of sugar beet (*Beta vulgaris*). Mahlein et al. (2013) have developed SDIs and Healthy Index (HI) for screening sugar beet foliage disease using a single waveband and normalized waveband differences. The works of Mahlein et al. (2012a; 2013) have motivated this work of developing a spectral index for OS disease. Diagnosis of plant diseases caused by fungi, bacteria and viruses using hand-held spectroradiometer is not new. However, the application of a hand-held spectroradiometer to study plant disease caused by viroids is new, particularly in oil palm.

In this research, oil palm seedlings were inoculated with a CCCVd oil palm variant (OP_{246}). This research was designed to observe the spectral changes between CCCVd-inoculated and healthy oil palm seedlings followed by development of spectral signatures, selection of red edge wavebands, selection of red edge indices and development of the OSDI using red edge parameters.

It is further noted that every new technique has its own merits and demerits. Every oil palm grower cannot be an expert on sensor application, data processing and data interpretation. Another concern is one needs to be proficient in developing indices from spectral wavebands. Several researchers have proposed several indices for disease detection rather than completely rely on spectral signatures. A spectral index plays an important role in data-dimensionality reduction and data analysis. Nonetheless, a long distance yet to cover for popularising the use of spectroradiometer for OS disease detection. The major issues are availability, affordability and applicability of the spectroradiometer.

1.5 Objectives

1. To measure spectral reflectance from CCCVd-inoculated and healthy oil palm seedlings and select optimal red edge wavebands and indices that offer maximum information for diagnosis of OS disease
2. To develop OSDI based on the red edge parameters for discriminating between diseased and healthy oil palm seedlings
3. To verify OSDI values in a repeated experiment and test the performance and efficacy of OSDI in diagnosing OS disease

REFERENCES

Abdulridha, J., Ehsani, R., de Castro, A., 2016. Detection and differentiation between Laurel wilt disease, phytophthora disease, and salinity damage using a hyperspectral sensing technique. Agriculture. 6, 2–13. doi: 10.3390/agriculture6040056.

Ahmed, S.S.S.J., Santosh, W., Kumar, S., Thanka Christlet, T.H., 2010. Neural network algorithm for the early detection of Parkinson's disease from blood plasma by FTIR micro-spectroscopy. Vib. Spectrosc. 53, 181–188. doi:10.1016/j.vibspec.2010.01.019.

Alchanatis, V., Cohen, Y., 2011. Spectral and spatial methods for hyperspectral image analysis for estimation of biophysical and biochemical properties of agricultural crops. In: Thenkabail, P.S., Lyon, J.G., Huete, A. (Eds.), Hyperspectral Remote Sensing of Vegetation. CRC Press, pp. 289–305.

Almeida J.S., 2002. Predictive non-linear modeling of complex data by artificial neural networks. Curr. Opin. Biotechnol. 1, 72–76. doi: 10.1016/S0958-1669(02)00288-4.

Apan, A., Held, A., Phinn, S., Markley, J., 2004. Detecting sugarcane "orange rust" disease using EO-1 hyperion hyperspectral imagery. Int. J. Remote Sens. 25, 489–498. doi:10.1080/01431160310001618031.

ASD., 2010. FieldSpec® HandHeld 2™ Spectroradiometer User Manual.

ASD., 2016. FieldSpec®4 Hi-Res spectroradiometer User Guide.

Ashourloo, D., Matkan, A.A., Huete, A., Aghighi, H., Mobasheri, M.R., 2016. Developing an index for detection and identification of disease stages. IEEE Geosci. Remote Sens. Lett. 13, 851–855. doi:10.1109/LGRS.2016.2550529.

Ashourloo, D., Mobasheri, M., Huete, A., 2014. Developing two spectral disease indices for detection of wheat leaf rust (*Pucciniatriticina*). Remote Sens. 6, 4723–4740. doi:10.3390/rs6064723.

Ayala-Silva, T., Beyl, C.A., 2005. Changes in spectral reflectance of wheat leaves in response to specific macronutrient deficiency. Adv. Sp. Res. 35, 305–317.

Balabin, R.M., Smirnov, S.V., 2011. Variable selection in near-infrared spectroscopy: Benchmarking of feature selection methods on biodiesel data. Anal. Chim. Acta 692, 63–72. doi:10.1016/j.aca.2011.03.006.

Balasundram, S.K., Kassim, F.A., Vadamalai, G., Hanif, A.H.M., 2013. Estimation of red tip disease severity in pineapple using a non-contact sensor approach. Agric. Sci. 4, 206–208. doi:10.4236/as.2013.44029.

Beltrán-Peña, H., Soria-Ruiz, J., Téliz-Ortiz, D., Ochoa-Martínez, D.L., Nava-Díaz, C., Ochoa-Ascencio, S., 2014. Molecular and satellite spectral imaging detection of Avocado Sunblotch Viroid (ASBVd). Rev. Fitotec. Mex. 37, 21–29.

Berterretche, M., Hudak, A.T., Cohen, W.B., Maiersperger, T.K., Gower, S.T., Dungan, J., 2005. Comparison of regression and geostatistical methods for mapping Leaf Area Index (LAI) with Landsat ETM+ data over a boreal forest. Remote Sens. Environ. 96, 49–61. doi:10.1016/j.rse.2005.01.014.

Blackburn, G.A., 2007. Hyperspectral remote sensing of plant pigments. J. Exp. Bot. 58, 855–867. doi:10.1093/jxb/erl123.

Blackburn, G.A., 1999. Relationships between spectral reflectance and pigment concentrations in stacks of deciduous broadleaves. Remote Sens. Environ. 70, 224–237. doi:10.1016/S0034-4257(99)00048-6.

Blackburn, G.A., 1998. Quantifying chlorophylls and careteniods at leaf and canopy scales. Remote Sens. Environ. 66, 273–285. doi:10.1016/S0034-4257(98)00059-5.

Blackmer, T.M., Schepers, J.S., Meyer, G.E., 1995. Remote sensing to detect nitrogen deficiency in corn. In: Proceedings of 2nd International Conference on Site-Specific Management for Agricultural Systems, Minneapolis, MN, USA, pp. 505–512. doi:10.2134/1995.site-specificmanagement.c35.

Boochs, F., Kupfer, G., Dockter, K., Kuhbauch, W., 1990. Shape of the red edge as vitality indicator for plants. Int. J. Remote Sens. 11, 1741–1753. doi:10.1080/01431169008955127.

Broge, N.H., Leblanc, E., 2001. Comparing prediction power and stability of broadband and hyperspectral vegetation indices for estimation of green leaf area index and canopy chlorophyll density. Remote Sens. Environ. 76, 156–172. doi:10.1016/S0034-4257(00)00197-8.

Bürling, K., Mauricio, H., Georg N., 2011. Use of blue-green and chlorophyll fluorescence measurements for differentiation between nitrogen deficiency and pathogen infection in winter wheat. J. Plant Physiol. 168, 1641–48.

Carter, G.A., 1991. Primary and secondary effects of water content on the spectral reflectance of leaves. Am. J. Bot. 78, 916. doi:10.2307/2445170.

Carter, G.A., Knapp, A.K., 2001. Leaf optical properties in higher plants: Linking spectral characteristics to stress and chlorophyll concentration. Am. J. Bot. 88, 677. doi:10.2307/2657068.

Carter, G.A., Miller, R.L., 1994. Early detection of plant stress by digital imaging within narrow stress-sensitive wavebands. Remote Sens. Environ. 50, 295–302. doi:10.1016/0034-4257(94)90079-5.

Chaerle, L., Hagenbeek, D., De Bruyne, E., Van Der Straeten, D., 2004. Thermal and chlorophyll-fluorescence imaging distinguish plant-pathogen interactions at an early stage. Plant Cell Physiol. 45, 887–896. doi:10.1093/pcp/pch097.

Chaerle, L., Hagenbeek, D., De Bruyne, E., Van Der Straeten, D., 2007. Chlorophyll fluorescence imaging for disease-resistance screening of sugar beet. Plant Cell. Tissue Organ Cult. 91, 97–106. doi:10.1007/s11240-007-9282-8.

Chappelle, E.W., Kim, M.S., McMurtrey, J.E., 1992. Ratio analysis of reflectance spectra (RARS): An algorithm for the remote estimation of the concentrations of chlorophyll A, chlorophyll B, and carotenoids in soybean leaves. Remote Sens. Environ. 39, 239–247. doi:10.1016/0034-4257(92)90089-3.

Cho, M.A., Skidmore, A.K., 2006. A new technique for extracting the red edge position from hyperspectral data: The linear extrapolation method. Remote Sens. Environ. 101, 181–193. doi:10.1016/j.rse.2005.12.011.

Clevers, J.G.P.W., De Jong, S.M., Epema, G.F., Van Der Meer, F.D., Bakker, W.H., Skidmore, A.K., Scholte, K.H., 2002. Derivation of the red edge index using the MERIS standard band setting. Int. J. Remote Sens. 23, 3169–3184. doi: 10.1080/01431160110104647.

Clevers, J.G.P.W., Kooistra, L., Salas, E.A.L., 2004. Study of heavy metal contamination in river floodplains using the red-edge position in spectroscopic data. Int. J. Remote Sens. 25, 3883–3895. doi:10.1080/01431160310001654473.

Curran, P.J., 1989. Remote sensing of foliar chemistry. Remote Sens. Environ. 30, 271–278. doi:10.1016/0034-4257(89)90069-2.

de Alba, A.E.M., Flores, R., Hernández. C., 2002. Two chloroplastic viroids induce the accumulation of small RNAs associated with posttranscriptional gene silencing. J. Virol. 76, 13094–13096.

Daròs, J.-A., 2016. Viroids: small noncoding infectious RNAs with the remarkable ability of autonomous replication, in: Current Research Topics in Plant Virology. Springer International Publishing, Cham, pp. 295–322. doi:10.1007/978-3-319-32919-2_13.

Darvishzadeh, R., 2008. Hyperspectral remote sensing of vegetation parameters using statistical and physical models. PhD Thesis, Wageningen Univ. Netherlands.

Darvishzadeh, R., Skidmore, A., Schlerf, M., Atzberger, C., Corsi, F., Cho, M., 2008. LAI and chlorophyll estimation for a heterogeneous grassland using hyperspectral measurements. ISPRS J. Photogramm. Remote Sens. 63, 409–426. doi:10.1016/j.isprsjprs.2008.01.001.

Delalieux, S., Somers, B., Verstraeten, W.W., Van Aardt, J.A.N., Keulemans, W., Coppin, P., 2009. Hyperspectral indices to diagnose leaf biotic stress of apple plants, considering leaf phenology. Int. J. Remote Sens. 30, 1887–1912.

Demetriades-Shah, T.H., Steven, M.D., 1988. High spectral resolution indices for monitoring crop growth and chlorosis, in: Spectral Signatures of Objects in Remote Sensing. p. 299.

Diem, M., Papamarkakis, K., Schubert, J., Bird, B., Romeo, M.J., Miljković, M., 2009. The infrared spectral signatures of disease: extracting the distinguishing spectral features between normal and diseased states. Appl. Spectrosc. 63, 307A–318A.

Diener, T.O., 2003. Timeline: discovering viroids — a personal perspective. Nat. Rev. Microbiol. 1, 75–80. doi:10.1038/nrmicro736.

Diener, T.O., 1999. Viroids and the nature of viroid diseases*, in: 100 Years of Virology. Springer Vienna, Vienna, pp. 203–220. doi:10.1007/978-3-7091-6425-9_15.

FAO, 2009. Declaration of the world summit on food security, Rome, 16-18 November.

Feng, W., Guo, B.-B., Wang, Z.-J., He, L., Song, X., Wang, Y.-H., Guo, T.-C., 2014. Measuring leaf nitrogen concentration in winter wheat using double-peak spectral reflection remote sensing data. F. Crop. Res. 159, 43–52. doi:10.1016/j.fcr.2014.01.010.

Ferwerda, J.G., 2005. Charting the quality of forage: measuring and mapping the variation of chemical components in foliage with hyperspectral remote sensing. PhD Thesis, Wageningen Univ. Netherlands.

Filella, I., Penuelas, J., 1994. The red edge position and shape as indicators of plant chlorophyll content, biomass and hydric status. Int. J. Remote Sens. 15, 1459–1470. doi:10.1080/01431169408954177.

Forde, S.C.M., Leyritz, M.J.P., 1968. A study of confluent orange spotting of the oil palm in Nigeria. J Niger Inst Oil Palm Res. 4, 371–380.

Fourty, T., Baret, F., Jacquemoud, S., Schmuck, G., Verdebout, J., 1996. Leaf optical properties with explicit description of its biochemical composition: direct and inverse problems. Remote Sens. Environ. 56, 104–117.

Gamon, J.A., Surfus, J.S., 1999. Assessing leaf pigment content and activity with a reflectometer. New Phytol. 143, 105–117. doi:10.1046/j.1469-8137.1999.00424.x.

Gausman, H.W., 1977. Reflectance of leaf components. Remote Sens. Environ. 6, 1–9.

Gilabert, M., Amparo, S. G., Joaquín M., 1996. Analyses of spectral-biophysical relationships for a corn canopy. Remote Sens. Environ. 55, 11–20.

Gitelson, A., 2011. Nondestructive estimation of foliar pigment (Chlorophylls, Carotenoids, and Anthocyanins) contents. In: Thenkabail, P.S., Lyon, J.G., Huete, A. (Eds.), Hyperspectral Remote Sensing of Vegetation. CRC Press, pp. 141–166. doi:10.1201/b11222-11.

Gitelson, A.A., Keydan, G.P., Merzlyak, M.N., 2006. Three-band model for noninvasive estimation of chlorophyll, carotenoids, and anthocyanin contents in higher plant leaves. Geophys. Res. Lett. 33, 1–5. doi:10.1029/2006GL026457.

Goetz, A.F.H., Vane, G., Solomon, J.E., Rock, B.N., 1985. Imaging spectrometry for earth remote sensing. Science 228, 1147–1153. doi:10.1126/science.228.4704.1147.

Golhani, K., Balasundram, S.K., Vadamalai, G., Pradhan, B., 2018. A review of neural networks in plant disease detection using hyperspectral data. Information Processing in Agriculture. 5, 354–371. doi: 10.1016/j.inpa.2018.05.002.

Golhani, K., Balasundram, S.K., Vadamalai, G., Pradhan, B., 2018. Use of reflectance spectroscopy as a tool for screening viroid-inoculated oil palm seedlings. Open Access Journal of Agricultural Research. 2, 2–5.

Grisham, M.P., Johnson, R.M., Zimba, P. V., 2010. Detecting Sugarcane yellow leaf virus infection in asymptomatic leaves with hyperspectral remote sensing and associated leaf pigment changes. J. Virol. Methods 167, 140–145. doi:10.1016/j.jviromet.2010.03.024.

Guyot, G., Baret, F., Jacquemoud, S., 1992. Imaging spectroscopy for vegetation studies. In: Toselli, F., Bodechtel, J. (Eds.), Imaging Spectroscopy: Fundamentals and Prospective Application. Kluwer Academic Publishers, Dordrecht, pp. 145–165.

Hanold, D., Randles, J.W., 1991a. Coconut cadang-cadang disease and its viroid agent. Plant Dis. 75, 330. doi:10.1094/PD-75-0330.

Hanold, D., Randles, J.W., 1991b. Detection of coconut cadang-cadang viroid-like sequences in oil and coconut palm and other monocotyledons in the south-west Pacific. Ann. Appl. Biol. 118, 139–151. doi:10.1111/j.1744 7348.1991.tb06092.x.

Hanold D., Randles J.W., 2003. CCCVd-related molecules in oil palms, coconut palms and other monocotyledons outside the Philippines. In: Hadidi A, Flores R, Randles J.W., Semancik J.S. (Eds.),Viroids. CSIRO Publishing, Australia, pp 336–344.

Helland, I.S., 2001. Some theoretical aspects of partial least squares regression. Chemom. Intell. Lab. Syst. 58, 97–107. doi:10.1016/S0169-7439(01)00154-X.

Hodgson, R.A.J., Wall, G.C., Randles, J.W.,1998. Specific identification of coconut tinangaja viroid for differential field diagnosis of viroids in coconut palm. Phytopathology 88, 774–781. doi:10.1094/PHYTO.1998.88.8.774.

Holzer, C., Precht, M., 1992. Multiple comparison procedures for normally distributed ANOVA models in SAS, SPSS, BMDP, and MINITAB. Comput. Stat. Data Anal. 13, 351–358. doi:10.1016/0167-9473(92)90141-2.

Horler, D.N.H., Dockray, M., Barber, J., 1983. The red edge of plant leaf reflectance. Int. J. Remote Sens. 4, 273–288. doi:10.1080/01431168308948546.

Horst, R.K., 2013 Viruses, Viroids, Phytoplasmas. In *Westcott's Plant Disease Handbook*, Dordrecht: Springer Netherlands, 49–54.

Huang, Y., 2009. Advances in artificial neural networks - methodological development and application." Algorithms. 2, 973–1007.

Huete, A.R., 1989. Soil influences in remotely sensed vegetation-canopy spectra, in: Asrar, G. (Ed.), Theory and Applications of Optical Remote Sensing. Wiley-Interscience New York, pp. 107–141.

Imperical, J.S., Bautista, R.M., Randles, J.W., 1985. Transmission of the coconut cadang-cadang viroid to six species of palm by inoculation with nucleic acid extracts. Plant Pathol. 34, 391–401. doi:10.1111/j.1365-3059.1985.tb01378.x.

Indahl, U.G., 2014. The geometry of PLS1 explained properly: 10 key notes on mathematical properties of and some alternative algorithmic approaches to PLS1 modelling. J. Chemom. 28, 168–180. doi:10.1002/cem.2589.

Iounousse, J., Er-Raki, S., El Motassadeq, A., Chehouani, H., 2015. Using an unsupervised approach of Probabilistic Neural Network (PNN) for land use classification from multitemporal satellite images. Appl. Soft Comput. 30, 1–13. doi:10.1016/j.asoc.2015.01.037.

Izzuddin, M.A., Idris, A.S., Nisfariza, N.M., Ezzati, B., 2015. Spectral based analysis of airborne hyperspectral remote sensing image for detection of ganoderma disease in oil palm, in: Int'l Conference on Biological and Environmental Science (BIOES 2015). pp. 13–20.

Jackson, G., 2016. Oil palm genetic orange spotting (205), Pacific pests and pathogens - fact sheets (online). www.pestnet.org/fact_sheets/mini/index.htm (accessed 15.8.18).

Jacquemoud, S., Baret, F., 1990. PROSPECT: A model of leaf optical properties spectra. Remote Sens. Environ. 34, 75–91. doi:10.1016/0034-4257(90)90100-Z.

Ji, G., Huang, G., Yang, Z., Wu, X., Chen, X., Yuan, M., 2015. Using consensus interval partial least square in near infrared spectra analysis. Chemom. Intell. Lab. Syst. 144, 56–62. doi:10.1016/j.chemolab.2015.03.008.

Jiang, Z., Huete, A.R., Didan, K., Miura, T., 2008. Development of a two-band enhanced vegetation index without a blue band. Remote Sens. Environ. 112, 3833–3845. doi:10.1016/j.rse.2008.06.006

Jimenez, L.O., Landgrebe, D.A., 1999. Hyperspectral data analysis and supervised feature reduction via projection pursuit. IEEE Trans. Geosci. Remote Sens. 37, 2653–2667.

Jones, C.D., Jones, J.B., Lee, W.S., 2010. Diagnosis of bacterial spot of tomato using spectral signatures. Comput. Electron. Agric. 74, 329–335. doi:10.1016/j.compag.2010.09.008.

Jordan, C.F., 1969. Derivation of leaf-area index from quality of light on the forest floor. Ecology 50, 663–666. doi:10.2307/1936256.

Knipling, E.B., 1970. Physical and physiological basis for the reflectance of visible and near-infrared radiation from vegetation. Remote Sens. Environ. doi:10.1016/S0034-4257(70)80021-9.

Kokaly, R., 1999. Spectroscopic determination of leaf biochemistry using band-depth analysis of absorption features and stepwise multiple linear regression. Remote Sens. Environ. 67, 267–287. doi:10.1016/S0034-4257(98)00084-4.

Köksal, E.S., 2011. Hyperspectral reflectance data processing through cluster and PCA for estimating irrigation and yield related indicators. Agric. Water Manag. 98, 1317–1328. doi:10.1016/j.agwat.2011.03.014.

Krafft, C., Steiner, G., Beleites, C., Salzer, R., 2009. Disease recognition by infrared and raman spectroscopy. J. Biophotonics 2, 13–28. doi:10.1002/jbio.200810024.

Krezhova, D., Stoev, A., Maneva, S., 2015. Detection of biotic stress (*Venturia inaequalis*) caused by apple stem grooving virus in apple trees using hyperspectral reflectance analysis. Comptes rendus l'Académie Bulg. des Sci. 68, 175–182.

Kumar, L., Schmidt, K., Dury, S., Skidmore, A., 2002. Imaging spectrometry and vegetation science, in: Imaging Spectrometry. Springer, pp. 111–155.

Lacis, A.A., Hansen, J., 1974. A parameterization for the absorption of solar radiation in the earth's atmosphere. J. Atmos. Sci. 31, 118–133.

Lawrence, G.W., Kelley, A.T., King, R.L., Vickery, J., Lee, H.K., McLean, K.S., 2004. Remote sensing and precision nematicide applications for *Rotylenchulus reniformis* management in cotton, in: Nematology Monographs and Perspectives. Brill, Leiden, Netherlands, pp. 13–21.

Lee, K.M., Herrman, T.J., Lingenfelser, J., Jackson, D.S., 2005. Classification and prediction of maize hardness-associated properties using multivariate statistical analyses. J. Cereal Sci. 41, 85–93. doi:10.1016/j.jcs.2004.09.006.

Lee, W.S., Alchanatis, V., Yang, C., Hirafuji, M., Moshou, D., Li, C., 2010. Sensing technologies for precision specialty crop production. Comput. Electron. Agric. 74, 2–33. doi:10.1016/j.compag.2010.08.005.

Li, B., Liu, Z., Huang, J., Zhang, L., Zhou, W., Shi, J., 2009. Hyperspectral identification of rice diseases and pests based on principal component analysis and probabilistic neural network. Trans. CSAE. 25, 143–147. doi: 10.3969/j.issn.1002-6819.2009.09.026.

Li, L., Ren, T., Ma, Y., Wei, Q., Wang, S., Li, X., Cong, R., Liu, S., Lu, J., 2016. Evaluating chlorophyll density in winter oilseed rape (*Brassica napus* L.) using canopy hyperspectral red-edge parameters. Comput. Electron. Agric. 126, 21–31. doi:10.1016/j.compag.2016.05.008.

Li, L., Ustin, S.L., Lay, M., 2005. Application of AVIRIS data in detection of oil-induced vegetation stress and cover change at Jornada, New Mexico. Remote Sens. Environ. 94, 1–16. doi:10.1016/j.rse.2004.08.010.

Lichtenthaler, H.K., 1996. Vegetation stress: an introduction to the stress concept in plants. J. Plant Physiol. 148, 4–14. doi:10.1016/S0176-1617(96)80287-2.

Lingjaerde, O.C., Christophersen, N., 2000. Shrinkage structure of partial least squares. Scand. J. Stat. 27, 459–473. doi:10.1111/1467-9469.00201.

Liu, Z.-Y., Huang, J.-F., Wu, X.-H., Dong, Y.-P., 2007. Comparison of vegetation indices and red-edge parameters for estimating grassland cover from canopy reflectance data. J. Integr. Plant Biol. 49, 299–306. doi:10.1111/j.1744-7909.2007.00401.x.

Mahlein, A.K, 2010. Detection, identification and quantification of fungal diseases of sugar beet leaves using imaging and non-imaging hyperspectral techniques. PhD Thesis, University of Bonn, Germany.

Mahlein, A.K., 2016. Plant disease detection by imaging sensors – parallels and specific demands for precision agriculture and plant phenotyping. Plant Dis. 100, 241–251. doi:10.1094/PDIS-03-15-0340-FE.

Mahlein, A.K., Steiner, U., Hillnhütter, C., Dehne, H.-W., Oerke, E.-C., 2012a. Hyperspectral imaging for small-scale analysis of symptoms caused by different sugar beet diseases. Plant Methods 8, 3. doi:10.1186/1746-4811-8-3.

Mahlein, A.K., Oerke, E.-C., Steiner, U., Dehne, H.-W., 2012b. Recent advances in sensing plant diseases for precision crop protection. Eur. J. Plant Pathol. 133, 197–209. doi:10.1007/s10658-011-9878-z.

Mahlein, A.K., Rumpf, T., Welke, P., Dehne, H.-W., Plümer, L., Steiner, U., Oerke, E.-C., 2013. Development of spectral indices for detecting and identifying plant diseases. Remote Sens. Environ. 128, 21–30. doi:10.1016/j.rse.2012.09.019.

Marini, F., Bucci, R., Magrì, A.L., Magrì, A.D., 2008. Artificial neural networks in chemometrics: history, examples and perspectives. Microchem. J. 88, 178–185. doi:10.1016/j.microc.2007.11.008.

Marini, F., Magrì, A.L., Bucci, R., 2007. Multilayer feed-forward artificial neural networks for class modeling. Chemom. Intell. Lab. Syst. 88, 118–124. doi:10.1016/j.chemolab.2006.07.004.

Marini, F., Zupan, J., Magrì, A.L., 2005. Class-modeling using kohonen artificial neural networks. Anal. Chim. Acta 544, 306–314. doi:10.1016/j.aca.2004.12.026.

Martens, H., 2001. Reliable and relevant modelling of real world data: a personal account of the development of PLS regression. Chemom. Intell. Lab. Syst. 58, 85–95. doi: 10.1016/S0169-7439(01)00153-8.

Merzlyak, M.N., Gitelson, A.A., Chivkunova, O.B., Solovchenko, A.E., Pogosyan, S.I., 2003. Application of reflectance spectroscopy for analysis of higher plant pigments. Russ. J. plant Physiol. 50, 704–710.

Milton, N.M., B.A. Eiswerth, C.M. Ager., 1991. Effect of phosphorus deficiency on spectral reflectance and morphology of soybean plants. Remote Sens. Environ. 36, 121–27. doi:10.1016/0034-4257(91)90034-4.

Mohanty S.P., Hughes D.P., Salathé M., 2016. Using deep learning for image-based plant disease detection. Front. Plant. Sci. 7, 1–10. doi:10.3389/fpls.2016.01419.

Monteiro, S.T., Kosugi, Y., Uto, K., Watanabe, E., 2004. Towards applying hyperspectral imagery as an intraoperative visual aid tool. In: Proceedings of the 4th IASTED International Conference on Visualization, Imaging and Image Processing, Marbella, Spain, pp. 483–488.

Moshou, D., Bravo, C., West, J., Wahlen, S., McCartney, A., Ramon, H., 2004. Automatic detection of 'yellow rust'in wheat using reflectance measurements and neural networks. Comput. Electron. Agric. 44, 173–188. doi:10.1016/j.compag.2004.04.003.

MPOB, 2018. Overview of the Malaysian oil palm industry 2017 (online). http://palmoilis.mpob.gov.my/index.php/overview-of-industry (accessed 7.8.18).

Noujdina, N. V, Ustin, S.L., 2008. Mapping downy brome (*Bromus tectorum*) using multidate AVIRIS data. Weed Sci. 56, 173–179.

Odabas, M.S., Simsek, H., Lee, C.W., İseri, İ, 2017. Multilayer perceptron neural network approach to estimate chlorophyll concentration index of Lettuce (*Lactuca Sativa* L.). Comm Soil Sci Plant Anal. 48, 162–69.

Oerke, E-C., Roland G., Gunter M., Richard A. S., 2010. Preface. In: Oerke, E-C., Roland G., Gunter M., Richard A. S. (Eds.), Precision Crop Protection-The Challenge and Use of Heterogeneity. Dordrecht, Netherlands: Springer, pp. vi–viii.

Owens, R., Flores, R., Di Serio, F., Li, S., Pallás, V., Randles, J., Sano, T., Vidalakis, G., 2012. Virus Taxonomy—ninth report of the International Committee on Taxonomy of Viruses. Elsevier, Academic Press, London, UK.

Paydipati, R., 2004. Evaluation of clasifiers for automatic disease detection in citrus leaves machine vision. Master Thesis, Univ. Florida.

Peñuelas, J., Gamon, J.A., Fredeen, A.L., Merino, J., Field, C.B., 1994. Reflectance indices associated with physiological changes in nitrogen- and water-limited sunflower leaves. Remote Sens. Environ. 48, 135–146. doi:10.1016/0034-4257(94)90136-8.

Pinar, A., Curran, P.J., 1996. Grass chlorophyll and the reflectance red edge. Int. J. Remote Sens. 17, 351–357. doi:10.1080/01431169608949010.

Pinter Jr., P.J., Hatfield, J.L., Schepers, J.S., Barnes, E.M., Moran, M.S., Daughtry, C.S.T., Upchurch, D.R., 2003. Remote sensing for crop management. Photogramm. Eng. Remote Sens. 69, 647–664. doi:10.14358/PERS.69.6.647.

Pradhan, B., Lee S., 2007. Utilization of optical remote sensing data and GIS tools for regional landslide hazard analysis using an artificial neural network model. Front. Earth Sci. 14, 143–151. doi:10.1016/S1872-5791(08)60008-1.

Randles, J.W., 1998. CCCVd-related sequences in species other than coconut, in: Hanold D., Randles J.W. (Eds.), Report on ACIAR-funded research on viroids and viruses of coconut palm and other tropical monocotyledons 1985–1993. ACIAR working paper No. 51, Canberra, Australia, pp. 144–152.

Randles, J.W., Boccardo, G., Imperical, J.S., 1980. Detection of the cadang-cadang associated RNA in African oil palm and buri palm. Phytopathology 70, 185. doi:10.1094/Phyto-70-185.

Randles, J.W., Rodriguez, J.M.B., Hanold, D., Vadamalai, G., 2009. Coconut cadang-cadang viroid infection of african oil palm. Planter 85, 93–101.

Randles, J.W., Rodriguez, M.J.B., 2003. Coconut cadang-cadang viroid. In: Hadidi, A., Flores, R., Randles, J.W., Semancik, J.S. (Eds.), Viroids. Collingwood: CSIRO Publishing. pp. 233–241.

Riedell, W.E., Osborne, S.L., Hesler, L.S., Blackmer, T.M., 2000. Remote sensing of insect damage in wheat. In: Proceedings of the 5th International Conference on Precision Agriculture, Bloomington, Minnesota, USA, 16-19 July, 2000. pp. 1–11.

Robertson, J.S., Prendergast, A.G., Sly, J.M.A., 1968. Diseases and disorders of the oil palm (*Elaeis guineensis*) in West Africa. J. Niger. Inst. Oil Palm Res. 4, 381–409.

Rosso, P.H., Pushnik, J.C., Lay, M., Ustin, S.L., 2005. Reflectance properties and physiological responses of Salicornia virginica to heavy metal and petroleum contamination. Environ. Pollut. 137, 241–252. doi:10.1016/j.envpol.2005.02.025.

Rouse Jr, J.W., Haas, R.H., Deering, D.W., Harlan, J.C., 1974. Monitoring the vernal advancement and retrogradation (green wave effect) of natural vegetation, NASA/GSFC type III final report, Greenbelt, MD.

Rumpf, T., 2012. Finding spectral features for the early identication of biotic stress in plants. PhD Thesis, Rheinische Friedrich-Wilhelms-Universität Bonn.

Rumpf, T., Mahlein, A., Dörschlag, D., Plümer, L., 2009. Identification of combined vegetation indices for the early detection of plant diseases. In: Neale, C.M.U., Maltese, A. (Eds.), SPIE Europe Remote Sensing. pp. 747217. doi:10.1117/12.830525.

Sankaran, S., Mishra, A., Ehsani, R., Davis, C., 2010. A review of advanced techniques for detecting plant diseases. Comput. Electron. Agric. 72, 1–13. doi:10.1016/j.compag.2010.02.007.

Schellberg, J., Hill, M.J., Gerhards, R., Rothmund, M., Braun, M., 2008. Precision agriculture on grassland: Applications, perspectives and constraints. Eur. J. Agron. 29, 59–71.

Selvaraja, S., Balasundram, S.K., Vadamalai, G., Husni, M.H.A., 2013. Use of spectral reflectance to discriminate between potassium deficiency and orange spotting symptoms in oil palm (*Elaeis guineensis*). Life Sci. J. 10, 947–951.

Sladojevic, S., Arsenovic, M., Anderla, A., Culibrk D., Stefanovic, D., 2016. Deep neural networks based recognition of plant diseases by leaf image classification. Comput. Intell. Neurosci., 1–11. doi:10.1155/2016/3289801.

Slonecker, E., 2011. Analysis of the effects of heavy metals on vegetation hyperspectral reflectance properties. In: Thenkabail, P.S., Lyon, J.G., Huete, A. (Eds.), Hyperspectral Remote Sensing of Vegetation. CRC Press, pp. 561–578. doi:10.1201/b11222-33.

Society for General Microbiology, 2011. Combating plant diseases is key for sustainable crops (online). www.sciencedaily.com/releases/2011/04/110411194819.htm (accessed 2.8.16).

Stafford, J.V, 2000. Implementing precision agriculture in the 21st Century. J. Agric. Eng. Res. 76, 267–275. doi:10.1006/jaer.2000.0577.

Sundberg, R., 1999. Multivariate calibration—direct and indirect regression methodology. Scand. J. Stat. 26, 161–207.

Thanarajoo S.S., 2014. Rapid detection, accumulation and translocation of Coconut cadang-cadang viroid variants in oil palm. Ph.D Thesis, Universiti Putra Malaysia, Serdang, Malaysia.

Thanarajoo, S.S., Kong, L.L., Kadir, J., Lau, W.H., Vadamalai, G., 2014. Detection of Coconut cadang-cadang viroid (CCCVd) in oil palm by reverse transcription loop-mediated isothermal amplification (RT-LAMP). J. Virol. Methods 202, 19–23. doi:10.1016/j.jviromet.2014.02.024.

Thomas, S., Wahabzada, M., Kuska, M.T., Rascher, U., Mahlein, A.K., 2017. Observation of plant--pathogen interaction by simultaneous hyperspectral imaging reflection and transmission measurements. Funct. Plant Biol. 44, 23–34.

Vadamalai, G., 2005. An investigation of orange spotting disorder in oil palm. PhD Thesis, The University of Adelaide, Adelaide.

Vadamalai, G., Hanold, D., Rezaian, M.A., Randles, J.W., 2006. Variants of Coconut cadang-cadang viroid isolated from an African oil palm (*Elaies guineensis* Jacq.) in Malaysia. Arch. Virol. 151, 1447–1456. doi:10.1007/s00705-005-0710-y.

Vadamalai, G., Perera, A., Hanold, D., Rezaian, M.A., Randles, J.W., 2009. Detection of Coconut cadang-cadang viroid sequences in oil and coconut palm by ribonuclease protection assay. Ann. Appl. Biol. 154, 117–125. doi:10.1111/j.1744-7348.2008.00278.x.

Van Maanen, A., Xu, X.-M., 2003. Modelling plant disease epidemics, in: Epidemiology of Mycotoxin Producing Fungi. Springer Netherlands, Dordrecht, pp. 669–682. doi:10.1007/978-94-017-1452-5_2.

Verhoef, W., 1984. Light scattering by leaf layers with application to canopy reflectance modeling: The SAIL model. Remote Sens. Environ. 16, 125–141. doi:10.1016/0034-4257(84)90057-9.

Wahabzada, M., Mahlein, A.K., Bauckhage, C., Steiner, U., Oerke, E.-C., Kersting, K., 2016. Plant Phenotyping using probabilistic topic models: Uncovering the hyperspectral language of plants. Sci. Rep. 6, 22482. doi:10.1038/srep22482.

Wasukar, A.R., 2014. Artificial neural network – an important asset for future computing. Int. J. Res. Emerg. Sci. technoloy. 1, 28–34.

West, J.S., Bravo, C., Oberti, R., Lemaire, D., Moshou, D., McCartney, H.A., 2003. The potential of optical canopy measurement for targeted control of field crop diseases. Annu. Rev. Phytopathol. 41, 593–614. doi:10.1146/annurev.phyto.41.121702.103726.

West, J.S., Bravo, C., Oberti, R., Moshou, D., Ramon, H., McCartney, H.A., 2010. Detection of fungal diseases optically and pathogen inoculum by air sampling, in: Precision Crop Protection - the Challenge and Use of Heterogeneity. Springer Netherlands, Dordrecht, pp. 135–149. doi:10.1007/978-90-481-9277-9_9.

Wold, H., 1975. Soft modeling by latent variables: the nonlinear iterative partial least squares approach. Perspect. Probab. Stat. Pap. honour MS Bartlett 520–540.

Wu, C., Wang, L., Niu, Z., Gao, S., Wu, M., 2010. Nondestructive estimation of canopy chlorophyll content using Hyperion and Landsat/TM images. Int. J. Remote Sens. 31, 2159–2167.

Wu, Y.H., Cheong, L.C., Meon, S., Lau, W.H., Kong, L.L., Joseph, H., Vadamalai, G., 2013. Characterization of Coconut cadang-cadang viroid variants from oil palm affected by orange spotting disease in Malaysia. Arch. Virol. 158, 1407–1410. doi:10.1007/s00705-013-1624-8.

Xu, H. R., Ying, Y. B., Fu, X. P., Zhu, S. P., 2007. Near-infrared spectroscopy in detecting leaf miner damage on tomato leaf. Biosyst. Eng., 96, 447–457.

Yang, F., Li, J., Gan, X., Qian, Y., Wu, X., Yang, Q., 2010. Assessing nutritional status of *Festuca arundinacea* by monitoring photosynthetic pigments from hyperspectral data. Comput. Electron. Agric. 70, 52–59. doi:10.1016/j.compag.2009.08.010.

Yoder, B.J., Pettigrew-Crosby, R.E., 1995. Predicting nitrogen and chlorophyll content and concentrations from reflectance spectra (400–2500 nm) at leaf and canopy scales. Remote Sens. Environ. 53, 199–211. doi:10.1016/0034-4257(95)00135-N.

Zhao, X., 2012. Advances and technology in infrared spectroscopy. J. Anqing Teach Coll. 18, 94–97.

Zhu, H., Cen, H., Zhang, C., He, Y., 2016. Early detection and classification of tobacco leaves inoculated with tobacco mosaic virus based on hyperspectral imaging technique, in: 2016 ASABE Annual International Meeting. p. 1. doi:10.13031/aim.20162460422.