NEAR INFRARED CALIBRATIONS FOR RAPID SCREENING OF FOLIAR NITROGEN AND PHOSPHORUS IN *Eucalyptus pellita* F. Muell

By

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

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Eucalyptus pellita F. Muell. has become an important tree species in the forest plantations of South-East Asia, and in Malaysian Borneo in particular, to replace thousands of hectares of *Acacia mangium* Willd., which has suffered significant loss caused by *Ceratocystis manginecans* infection in Sabah, Malaysia.

Nitrogen (N) and phosphorus (P) fertilization at the time of planting are essential to optimize *E. pellita* establishment and growth in forest plantations. Traditionally, plant nutrient content is analyzed via wet chemistry methods using ground, dried foliar samples with the associated cost of analysis of many leaf samples. Generally, this chemical technique requires large amount of chemicals and reagents, which may be unfriendly to environment and hazardous to health.

This study aims to quantitatively estimate N and P elements in *E. pellita* foliage samples by means of near- infrared (NIR) reflectance spectroscopy. This method is non- destructive, rapid and cost-effective. In order to be used effectively, the NIR spectra must be calibrated with foliar samples that have also been analyzed using reference methods.

In this present study, the nutritional status of the foliage was investigated with the aim to develop near- infrared spectroscopic calibrations that can be used to monitor and quantify nutrient status, particularly total foliar nitrogen (N) and phosphorus (P) in the field. The spectrum data was captured using VIAVI 1700 hand-held spectrometer. Spectra acquired on fresh foliage in situ on the tree could be used to predict N and P with accuracy suitable for operational decision- making

with regards to fertilizer application. Accuracy of spectra acquired on dried ground foliage could be used to predict N and P within a relative error of 10% (R^2_c, r^2_{CV}, RMSEP, RPD of = 0.77, 0.71, 0.02 g. 100 g^{-1}, 1.9 for foliar P and = 0.90, 0.88, 0.21 g. 100 g^{-1}, 3.0 for foliar N on dried ground foliage).

Therefore, the ultimate application of this near-infrared spectroscopic calibration is in situ nutrient monitoring, particularly in longitudinal studies in fertilizer trial plots and forest operations, as the non-destructive nature of NIR spectroscopy would enable regular monitoring of individual leaves over time without the need to destructively sample them. This would aid the temporal and spatial analysis of field data.

Abstrak tesis ini disampaikan kepada Senat Universiti Putra Malaysia bagi memenuhi syarat untuk ijazah master sains

KALIBRASI INFRA MERAH DEKAT UNTUK SARINGAN PANTAS FOLIAR NITROGEN DAN FOSFORUS DALAM *Eucalyptus pellita* F. Muell

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Eucalyptus pellita F. Muell. telah menjadi spesies pokok yang penting di ladang hutan Asia Tenggara dan di Borneo Malaysia khususnya, untuk menggantikan beribu-ribu hektar *Acacia mangium* Willd. yang telah mengalami kerugian yang besar akibat serangan penyakit *Ceratocystis manginecans* di Sabah, Malaysia.

Pembajaan nitrogen (N) dan fosforus (P) pada masa penanaman adalah penting untuk mengoptimumkan kadar pertumbuhan *E. pellita* di ladang hutan. Secara tradisinya, kandungan nutrien tumbuhan dianalisis melalui kaedah bahan kimia menggunakan sampel daun kering yang dikisar dengan kos analisis yang memerlukan banyak sampel daun. Secara amnya, Teknik kimia ini memerlukan sejumlah besar bahan kimia dan reagen yang mungkin tidak mesra alam sekitar dan berbahaya kepada kesihatan.

Kajian ini bertujuan untuk menganggar secara kuantitatif bagi unsur N dan P dalam sampel daun *E. pellita* menggunakan spektroskopi pemantulan inframerah dekat (NIR). Kaedah ini tidak merosakkan, cepat dan kos efektif. Bagi menilai keberkesanan kaedah ini, spektrum NIR mesti ditentukur dengan sampel daun yang telah dianalisis menggunakan kaedah rujukan.

Dalam kajian ini, status nutrisi daun telah disiasat dengan tujuan untuk membangunkan penentukuran spektroskopi inframerah yang boleh digunakan untuk memantau dan mengukur status nutrien, terutamanya bagi jumlah nitrogen (N) dan fosforus (P) daun di ladang. Pengambilan data spektrum adalah menggunakan spektrometer VIAVI 1700. Spektrum yang diperoleh daripada daun segar “in situ” pada pokok boleh digunakan untuk meramalkan nilai N dan P dengan ketepatan yang sesuai untuk membuat keputusan operasi yang berkaitan

penggunaan baja. Jika ketepatan yang lebih tinggi diperlukan, spektrum yang diperoleh pada dedaun kering yang digiling boleh digunakan untuk meramalkan N dan P dimana ralat relatifnya adalah 10% (R^2_c, r^2_{CV}, RMSEP, RPD = 0.77, 0.71, 0.02 g. 100 g^{-1}, 1.9 untuk daun P dan = 0.90, 0.88, 0.21 g. 100 g^{-1}, 3.0 untuk dedaun N pada dedaun kering yang digiling).

Oleh itu, aplikasi kajian ini bagi pemantauan nutrien in situ, terutamanya untuk membantu kajian menyeluruh dalam percubaan baja dan operasi hutan, dimana kaedah spektroskopi NIR yang tidak merosakkan akan membolehkan pemantauan tetap daun secara individu dari masa ke masa tanpa merosakkan sampel. Ini juga akan membantu dalam analisis temporal dan spatial data di ladang.

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I am extremely indebted to my parents and my wife for fully supporting my Master's program. Without their support, I would not be able to enhance my knowledge, particularly in forest plantation management.

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LIST OF ABBREVIATIONS

AFC	Borneo Forestry Cooperative
Bhd	Berhad
cm	Centimeter
cm^{-1}	Reciprocal Centimeter
CRD	Completely Randomized Design
DBH	Diameter at Breast Height
EMSC	Extended Multiplicative Scatter Correction
FAO	Food and Agriculture Organization
$g.100g^{-1}$	Gram per Hundred Grams
ha	Hectare
i.e.	That is to say (Latin: i*d* est)
In	Indium
GaAs	Gallium Arsenide
IR	Infrared
Kg m^{-3}	Kilogram per Cubic Meter
LV LVF	Latent Variable Linear Variable Filter
m	Meter
m^3	Cubic Meter
m^3 ha^{-1} $year^{-1}$	Multiplicative Scatter Correction
mm	Milimeter
MAIV	Mean Annual Increment of Volume
MIR	Mid Infrared
MOE	Modulus of Elasticity
MSC	Multiplicative Scatter Correction
MTH	Mixed Tropical Hardwood
N	Nitrogen
NIR	Near Infrared

Nm	Nanometer
P	Phosphorus
PCA	Principal Component Analysis
pH	Potential of Hydrogen
PLS	Partial Least Squares
RCBD	Randomised Complete Block Design
RMSE	Root Mean Square Error
RMSEC	Root Mean Square Error of Calibration
RMSECV	Root Mean Square Error of Cross Validation
RMSEP	Root Mean Square Error of Prediction
RPD	Ratio of Prediction of Determination
SAFODA	Sabah Forest Development Authority
SD	Standard Deviation
SEC	Standard Error of Calibration
SEP	Standard Error of Prediction
Sdn	Sendirian
SG	Savitzky-Golay
SNV	Standard Normal Variate
Spha	Stems per Hectare
SSB	Sabah Softwoods Berhad
Tn	Treatment Number
YFEL	Young Fully Expanded Leaf
"	Inches
%	Percentage
>	More than
<	Less than

CHAPTER 1

INTRODUCTION

1.1 Background

Sabah forest industry has been reliant on raw wood acquired locally from natural forest stands for decades, also known as a mixed tropical hardwood (MTH). However, as natural forest harvest declines around the world, sustainably-managed forest plantations are gradually replacing this scenario as the primary source of wood supplies (FAO, 2020), prompting the increased expansion of forest plantations around the world.

The mission and vision of forest plantations varied markedly among regions. Nonetheless, the general consensus on establishing forest plantations is to provide raw materials for industrial timber processing operations, such as solid-wood products, panel products and furnishings, and pulpwood for paper. Forest plantations, also known as planted forests, were established to fulfill the global demand for timber products as a replacement for natural timber products. In 2000, forest plantations only made up 5% of global forest cover, but they produced 35% of global round-wood production (FAO, 2010; 2016). Globally, forest plantation area has increased by 1.85% per year on average since 1990, and is currently approaching 294 million hectares.

The greatest annual average increase occurred in North and Central America, South America, and Asia, with around 2.5%, 2.4% and 2.3%, respectively (FAO, 2020). Both Pinus species and Eucalyptus species have been deployed, to a point where Eucalypt trees occupy around 20 million hectares in more than 90 countries, with the largest plantation areas being in Brazil (more than seven million ha), India (more than six million ha), and China (more than five million ha) (Elli et al., 2019; Arnold et al., Japarudin et al., 2020).

Industrial tree plantation (ITP) in Malaysia began in the 1920's for research purposes (Selvaraj and Muhammad, 1980), with the then anticipated establishment of an integrated pulp and paper mill in Peninsular Malaysia in 1967, at which time the first large-scale commercial forest plantation was developed. Given the depleting availability of timber resources, the government turned its focus on expanding the forest plantations through Malaysia's afforestation program in the 1980's (Ratnasingam et al., 2020).

In the 1970's, the government of Sabah played a key role in establishing firms, mainly Sabah Softwoods Bhd. (SSB), the Sabah Forestry Development Authority (SAFODA), and Sabah Forest Industries Sdn. Bhd. (SFI) to spearhead the forest plantation program. As a result, four fast-growing hardwood species were chosen, such as *Acacia mangium* Willd., Gmelina arborea Roxb., *Falcataria moluccana* (Miq.) Barneby & J.W. Grimes (formerly known as *Albizia falcataria* (L.) Fosberg), and *Eucalyptus deglupta* Blume. Both *G. arborea* and *E. deglupta* were phased out in favour of *A. mangium* and *F. moluccana* (Sabah Forestry Department, undated).

Over the years, the timber industries in Sabah became more aware of the need for raw materials; hence, the expansion of the tree plantation areas with approximately 55,560 ha of A. mangium had been established by 2002 (Krishnapillay, 2002), which then further increased to 75,120 ha by 2004 (Hashim et al., 2015). In the excitement of increasing production, the forest plantation industry, however, was shocked by the infestation of *Ceratocystis manginecens* fungi (vascular wilt disease) on *A. mangium* plantations (Tarigan et al., 2010; 2011; Brawner et al., 2015). This has led to the focus on increased research and understanding of Eucalyptus as an alternative species. While there are more than 700 varieties of Eucalyptus, only a dozen or so species are deployed in commercial tree plantations, particularly in tropical regions to continuously provide wood product. Interestingly, this genus has a wide range of adaptation based on species variety, for example, *Eucalyptus nitens* and *E. globulus* are more suitable in temperate regions, while *E. pellita*, *E. urophylla* and *E. camaldulensis* are adapted to tropical and sub-tropical regions. Nowadays, the utilization of Eucalyptus has been proven in Asia, where Eucalyptus plantations have increased in a number of countries, particularly India, China, Vietnam and Thailand, where they support major fundamentals to the industries and contribute to mitigation of rural poverty (FAO, 2020).

The development of Eucalyptus plantations, particularly *E. pellita,* is influenced by the quality of the planting materials and silviculture practices, such as nutrition management. Generally, nutrition management is essential when planting tree seedlings in commercial Eucalyptus plantations. By highlighting the growth limitation factor, nutrients such as Nitrogen (N) and Phosphorus (P) are crucial depending on the site condition (Garciano et al., 2006; Inail et al.; Crous et al., 2015; 2019)., and iIt is a viable silvicultural method for increasing stand nutrient availability (Schonau et al., 1989, Fox et al., 2007, Viera et al., 2016).

Eucalyptus pellita F. Muell., also known as red mahogany, occurs naturally in the tropical regions of north-eastern Queensland, Australia and the island of New Guinea. It grows in gentle to moderate sloping terrain mixed with other eucalypt species in tall open forest and at the fringes to tropical rainforest. It prefers sand to loam soil types with good drainage at altitudes from sea level to 800 m asl with moderate to high rainfall of 900 to 4000 mm annually (Brooker and Kleinig, 2012). It is one of the few eucalyptus species that is adapted to the wet tropical climate and is thus less susceptible to fungal leaf pathogens (Harwood et al., 1997). This adaptation together with other positive traits make it suitable for plantation establishment in wet tropical regions outside of its natural range.

At planting stage, both N and P are generally applied, along with other macro- and micro- nutrients, in Eucalyptus plantations depending on the site and soil condition. To observe and quantify the response to these applications on the growth of trees over time, the collection of foliar samples is required to generate some information on the level of availability of the nutrients. In addition, before site establishment in the planted forest, weed control is crucial to reduce the competition in terms of nutrition and space to optimize tree growth (Alwi et al., 2020). However, there are several problems associated with monitoring foliar nutrition. The traditional analysis using wet chemical methods takes a long time, is destructive, has a high cost of analysis, and the consumption of chemical reagents is not environmentally friendly (Samborski et al., 2009; Minesatti et al., 2010).

As an alternative method to monitor and evaluate the nutrition elements in the trees, this study focused on the development of a Near- Infrared (NIR) spectroscopic method for the rapid, cost-effective determination of nutritional nitrogen and phosphorus in *E. pellita* foliage. Studies have been undertaken using this method to quantify and qualify nitrogen and phosphorus in agriculture, pharmaceutical, and soil, however, no evidence has been found for NIR application in *E. pellita* plant nutrition, particularly on specific nutrients such as N and P.

1.2 Statement of Problems and Justifications

Nitrogen (N) and phosphorus (P) are the two macro-elements that influence the initial growth of plants among the seventeen essential nutrients required (Elser et al., 2007; Harpole et al., 2011), particularly in *E. pellita* due to their key roles in many cellular functions of plant metabolism (Inail et al., 2019). Generally, foliar chemical analysis is the main option in forestry to determine the nutritional plant status in conjunction with soil chemical analysis. Traditionally, foliar chemical analysis is used to obtain the nutrients information, however, it is challenging because of the destructive nature of the sampling, which makes it impossible to track individual leaves over time, making longitudinal investigations impossible. "Matched pairs" or bulked samples are employed instead of monitoring an individual leaf (or leaves) over time, which increases sampling errors related to sample representation and heterogeneity (Esbensen, 2019).

The capacity to monitor the foliar response over time to correlate nutrient status with tree growth will considerably help research into the nutritional response of plantation tree species such as *E. pellita*. However, traditional foliar chemical analysis requires a large number of samples for analysis, which is not only time-consuming and, expensive, but also has a negative impact on the environment due to the chemical reagents used during the chemical analysis in the laboratory (Kiwfo et al., 2021).

Near-infrared (NIR) spectroscopy has great potential for rapid and real-time, non- destructive determination of N and P in foliage, and can offer high throughput analysis at a lower- cost for the element of interest (Prananto et al., 2021). As recently evaluated by multiple academics globally, the growing number of publications on this technique and the worldwide adoption of this technology by several research organizations indicated the growing interest in NIR spectroscopy application in bio analysis. However, in order to accurately estimate the concentration of targeted elements in a sample using NIR spectroscopy, the spectral analysis must first be calibrated (Agelet and Hurburgh, 2010) and validated against the spectral absorption of targeted elements of the foliar samples, in which this study aimed for the elements of nitrogen (N) and phosphorus (P). One way to obtain this value data set is to establish fertilizer trials at nursery and field stages and review the results once they are fully assessed to validate the range across the stages.

Another issue in determining the reliability of NIR calibration is the condition of samples with high moisture content (water) levels or samples analyzed in the field, because the fundamental of NIR spectroscopy applications is predominantly based on the use of dry and ground samples (Malley et al., 2004). In the NIR region, water contains intense absorption bands, with the major absorptions between 1400 and 1900 nm (Roberts and Cozzolino, 2017). The presence of water in samples tends to lower the sample’s reflective index, resulting in less scattering of light incidence (Minasny et al., 2011; Ogen et al., 2019). Thus, the sample's spectral pre-processing and physical state (either dry or fresh) are crucial factors that determine the accuracy of the analysis in relation to the target outcome.

The spectral data are measured using a spectrometer. In this study, a hand-held spectrometer was used, which is known widely as the Micro-NIR 1700. The Micro- NIR 1700 (Viavi Solutions Inc., Milpitas, CA, USA) spectrometer comprises the light source, collection optics, electronics, and detector in a device that is less than 2 "- in diameter (50 mm) and weighs 58 g, using Viavi linear variable filter (LVF) technology as the dispersion element. An LVF is a band-pass filter coating intentionally wedged in one direction. As a result of the varying film thickness, the wavelength transmitted through the filter varies linearly in the direction of the wedge. The LVF is coupled to a linear detector array (128-pixel uncooled InGaAs photodiode array). The light source is a pair of integrated vacuum tungsten lamps. A 16-bit analogue-to-digital converter (ADC) is used for the analogue conversion, as shown in Figure 1.1. This spectrometer can be used in diffuse reflection, transmission, or transflection modes powered by USB.

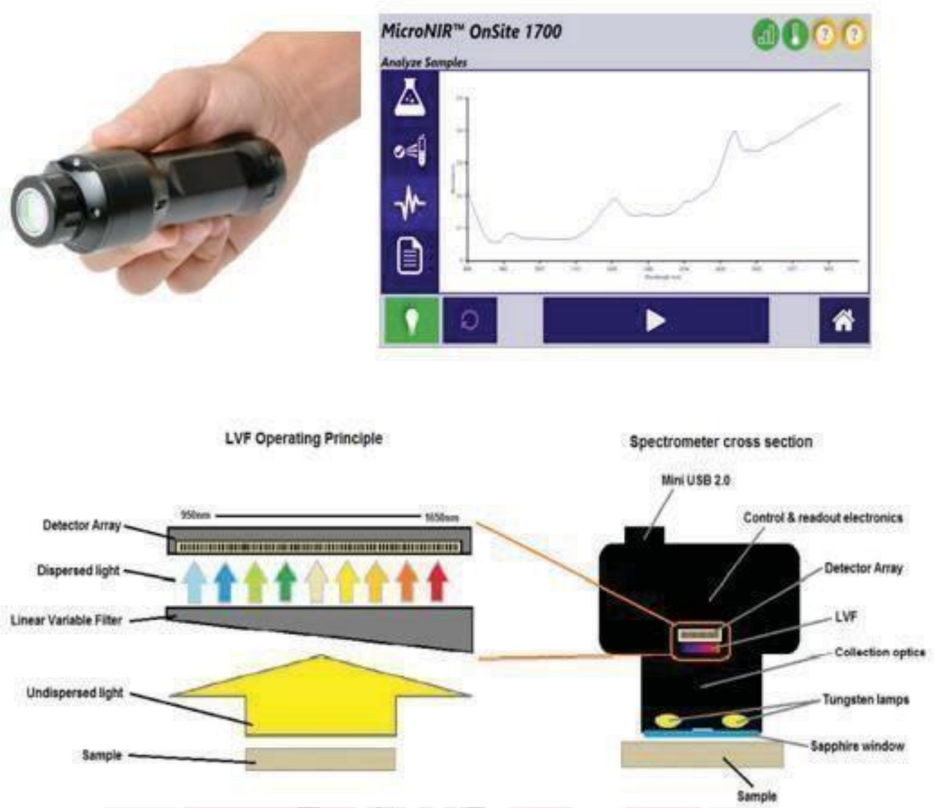

Figure 1.1: Overview of spectrometer, (a) the MicroNIR™ spectrometer (Viavi Solutions Inc., Milpitas, CA, USA), (b) an example of spectrum captured from sample, and (c) overview of MicroNIR sections.
(Source: www.viavisolution.com)

1.3 Objectives

This study aimed to develop NIR spectral calibrations for the determination of foliar nitrogen (N) and phosphorus (P) in *E. pellita*. The specific objectives of this study were:

i) to predict foliar N and P in *E. pellita* based on robust NIR spectral calibrations,
ii) to improve the nutrient level monitoring, particularly N and P, through foliar assessment, and
iii) to develop low-cost and fast methods for foliar N and P monitoring.

The information from this study will help to improve the nutrient management of *E. pellita* tree plantations and may enhance productions. This is important in diagnosing the nutrient level in a forest plantation.

1.4 Organization of Chapters

This thesis contains the following chapters:

Chapter 1: Introduction

The introduction summarizes and outlines the current state of forest plantation, both globally and in Malaysia (with particular emphasis in Sabah), and the key research problems met by this study.

Chapter 2: Literature review

This chapter presents an overview of the Eucalyptus plantation, information on species studied, and an insight into the theory and fundamentals of Near-Infrared spectroscopy. The literature review examines the conventional laboratory techniques analysis based on foliar (plant tissue) used in this project, and mathematical (chemometrics) techniques applicable to predict the value of nitrogen and phosphorus using through fresh and dry-ground samples of *E. pellita* foliage.

Chapter 3: Methodology

This chapter elaborates on the strategies employed in this research to achieve the objectives, with a detailed description of the study site, spectrometer as the (tool), and methodologies of foliar sample selection and preparation, N and P chemical analysis, spectroscopic and analytical techniques used in the assessment of calibration model development.

Chapter 4: Results and discussion

This chapter presents the results obtained for N and P of fresh and dry-ground *E. pellita* foliage, their correlation with NIR spectra and the calibration development and validation.

Chapter 5: Conclusions and recommendation

This chapter summarizes the results of the study and indicates how these results have fulfilled the objective of this study. It also consolidates the outcome and benefits to the industries, particularly in the nutrition management of *E. pellita.*

REFERENCES

Abe, H., Watanabe, K., Ishikawa, A., Noshiro, S., Fujii, T., Iwasa, M., & Wada, H. (2016). Simple separation of *Torreya nucifera* and *Chamaecyparis obtusa* wood using portable visible and near-infrared spectrophotometry: differences in light-conducting properties. Journal of Wood Science, 62(2), 210-212.

Abrams, S. M., Shenk, J. S., Westerhaus, M. O., & Barton II, F. E. (1987). Determination of forage quality by near infrared reflectance spectroscopy: efficacy of broad-based calibration equations. Journal of dairy science, 70(4), 806-813. doi: 10.3168/jds.S0022-0302(87)80077-2

Aenugu, H. P. R., Kumar, D. S., Srisudharson, N. P., Ghosh, S. S., & Banji, D. (2011). Near infra-red spectroscopy-an overview. International Journal of ChemTech Research, 3(2), 825-836.

Agelet, L. E., & Hurburgh Jr, C. R. (2010). A tutorial on near infrared spectroscopy and its calibration. Critical Reviews in Analytical Chemistry, 40(4), 246-260. doi: 10.1080/10408347.2010.515468

Agnew, R. E., Park, R. S., Mayne, C. S., & Laidlaw, A. S. (2004). Potential of near infrared spectroscopy to predict the voluntary intake of grazed grass. Animal Feed Science and Technology, 115(1-2), 169-178.

Alvarado, A. (2016). Plant Nutrition in Tropical Forestry. Tropical Forestry Handbook, 1113–1202. doi: 10.1007/978-3-642-54601-3_105

Alves, A., Santos, A., Rozenberg, P., Pâques, L. E., Charpentier, J. P., Schwanninger, M., & Rodrigues, J. (2012). A common near infrared—based partial least squares regression model for the prediction of wood density of *Pinus pinaster* and *Larix × eurolepis*. Wood Science and Technology, 46(1-3), 157-175. doi: 10.1007/s00226-010-0383-x

Alwi, A., Lapammu, M., Jarapudin, Y., Molony, K., Boden, D., Macdonell, P., Warburton, P., Brawner, J., & Meder, R. (2020). Importance of weed control prior to planting for the establishment of planted forests in Sabah, Malaysia. Journal of Tropical Forest Science, 32(4), 349–354.

Alwi, A., Meder, R., Japarudin, Y., Hamid, H. A., Sanusi, R., & Yusoff, K. H. M. (2021). Near infrared spectroscopy of *Eucalyptus pellita* for foliar nutrients and the potential for real-time monitoring of trees in fertiliser trial plots. Journal of Near Infrared Spectroscopy, 29(3), 158-167. doi: 10.1177/09670335211007971

Arnold, R. J., Xie, Y. J., Luo, J. Z., Wang, H. R., & Midgley, S. J. (2020). A tale of two genera: Exotic Eucalyptus and Acacia species in China. 2. Plantation resource development. International Forestry Review, 22(2),153-168.

Barnes, R. J., Dhanoa, M. S., & Lister, S. J. (1989). Standard normal variate transformation and de-trending of near-infrared diffuse reflectance spectra. Applied spectroscopy, 43(5), 772-777. doi: 10.1366/0003702894202201

Bart, M. N., Beullens, K., Bobelyn, E., Peirs, A., Saeys, W., Theron, K. I., & Lammertyn, J. (2007). Nondestructive measurement of fruit and vegetable quality by means of NIR spectroscopy: A review. Postharvest biology and technology, 46(2), 99– 118. doi: 10.1016/j.postharvbio.2007.06.024

Basri, K. N., Laili, A. R., Tuhaime, N. A., Hussain, M. N., Bakar, J., Sharif, Z., ... & Zoolfakar, A. S. (2018). FT-NIR, MicroNIR and LED-MicroNIR for detection of adulteration in palm oil via PLS and LDA. Analytical Methods, 10(34), 4143- 4151.doi: 10.1039/C8AY01239C

Berzaghi, P., Cherney, J. H., & Casler, M. D. (2021). Prediction performance of portable near infrared reflectance instruments using preprocessed dried, ground forage samples. Computers and Electronics in Agriculture, 182, 106013. doi: 10.1016/j.compag.2021.106013

Boland, D. J., Brooker, M. I. H., Chippendale, G. M., Hall, N., Hyland, B. P. M., Johnston, R. D., Kleinig, D. A., & Jurner, J. D. (1985). Forest trees of Australia. Melbourne: Nelson, CSIRO.

Bootle, K. R. (1983). Wood in Australia. Australia: McGraw-Hill.

Braga, J. W. B., Pastore, T. C. M., Coradin, V. T. R., Camargos, J. A. A., & da Silva, A. R. (2011). The use of near infrared spectroscopy to identify solid wood specimens of *Swietenia macrophylla* (Cites Appendix II). Iawa Journal, 32(2), 285-296.

Brawner, J., Japarudin, Y., Lapammu, M., Rauf, R., Boden, D., & Wingfield, M. J. (2015). Evaluating the inheritance of *Ceratocystis acaciivora* symptom expression in a diverse *Acacia mangium* breeding population. Southern Forests: a journal of forest science, 77(1), 83-90. doi: 10.2989/20702620.2015.1007412

Bray, R. H., & Kurtz, L. T. (1945). Determination of total, organic, and available forms of phosphorus in soils. Soil science, 59(1), 39-46.

Bristow, M., Vanclay, J. K., Brooks, L., & Hunt, M. (2006). Growth and species interactions of *Eucalyptus pellita* in a mixed and monoculture plantation in the humid tropics of north Queensland. Forest Ecology and Management, 233(2-3), 285-294. doi: 10.1016/j.foreco.2006.05.019.

Brooker, M. I. H., & Kleinig, D. A. (1983). Field guide to eucalypts. Volume 1. South-eastern Australia. Inkata Press Pty Ltd.

Cao, N. (2013). Calibration optimization and efficiency in near infrared spectroscopy (Doctoral dissertation, Iowa State University).

Chen, J., Gu, B., LeBoeuf, E. J., Pan, H., & Dai, S. (2002). Spectroscopic characterization of the structural and functional properties of natural organic matter fractions. Chemosphere, 48(1), 59-68. doi: 10.1016/s0045-6535(02)00041-3

Clark, D. H., Cary, E. E., & Mayland, H. F. (1989). Analysis of trace elements in forages by near infrared reflectance spectroscopy. Agronomy Journal, 81, 91-95.

Clark, D. H., Mayland, H. F., & Lamb, R. C. (1987). Mineral Analysis of Forages with near Infrared Reflectance Spectroscopy1. Agronomy Journal, 79(3), 485. doi: 10.2134/agronj1987.00021962007900030016x

Cooper, P. A., Jeremic, D., Radivojevic, S., Ung, Y. T., & Leblon, B. (2011). Potential of near-infrared spectroscopy to characterize wood products. Canadian Journal of Forest Research, 41(11), 2150-2157. doi: 10.1139/x11-088

Cozzolino, D., & Moron, A. (2004). Exploring the use of near infrared reflectance spectroscopy (NIRS) to predict trace minerals in legumes. Animal Feed Science and Technology, 111(1-4), 161-173. doi: 10.1016/j.anifeedsci.2003.08.001

Crous K. Y., Wujeska-Klause A, Jiang M, Medlyn B. E., & Ellsworth D. S. (2019) Nitrogen and phosphorus retranslocation of leaves and stemwood in a mature eucalyptus forest exposed to 5 years of elevated CO2. Frontiers in Plant Science, 10:664. doi: 10.3389/fpls.2019.00664

Crous, K. Y., Ósvaldsson, A., & Ellsworth, D. S. (2015). Is phosphorus limiting in a mature Eucalyptus woodland? Phosphorus fertilisation stimulates stem growth. Plant and Soil, 391(1-2), 293–305. doi: 10.1007/s11104-015-2426-4

Davies, A. M. C. (n. d.). An introduction to near infrared (NIR) spectroscopy. https://www.impopen.com

Dell, B., Xu, D., & Thu, P. Q. (2012). Managing threats to the health of tree plantations in Asia. New perspectives in plant protection. InTech, Rijeka, Croatia, 63-92.

Dombro, D. B. (2010). *Eucalyptus pellita*: Amazonia Reforestation's red mahogany. Bogotá: Planeta Verde Reforestación.

Downes, G. M., Harwood, C. E., Wiedemann, J., Ebdon, N., Bond, H., & Meder, R. (2012). Radial variation in Kraft pulp yield and cellulose content in *Eucalyptus globulus* wood across three contrasting sites predicted by near infrared spectroscopy. Canadian Journal of Forest Research, 42(8), 1577- 1586. doi: 10.1139/x2012-083

Easty, D. B., Berben, S. A., DeThomas, F. A., & Brimmer, P. J. (1990). Near-infrared spectroscopy for the analysis of wood pulp: quantifying hardwood-softwood mixtures and estimating lignin content. Tappi Journal, 73(10), 257-261.

Elli, E. F., Sentelhas, P. C., de Freitas, C. H., Carneiro, R. L., & Alvares, C. A. (2019). Assessing the growth gaps of Eucalyptus plantations in Brazil–Magnitudes, causes and possible mitigation strategies. Forest Ecology and Management, 451, 117464. doi: 10.1016/j.foreco.2019.117464

Elser, J. J., Bracken, M. E., Cleland, E. E., Gruner, D. S., Harpole, W. S., Hillebrand, H., & Smith, J. E. (2007). Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems. Ecology letters, 10(12), 1135-1142.

Esbensen, K. H., & Swarbrick, B. (2019). Sampling for spectroscopic analysis: Consequences for multivariate calibration. Spectroscopy. Europe, 3, 22-28.

FAO, (2010). Global Forest Resources Assessment 2010. Food and Agriculture Organization of the United Nations, Rome, Italy. ISBN: 978-92-5-106654- 6.

FAO, (2016). How are the world's forests changing? Global Forest Resources Assessment 2015, 2nd Edition. Food and Agriculture Organization of the United Nations, Rome, Italy. ISBN: 978-92-5-109283-5.

FAO, (2020). Global Forest Resources Assessment 2020: Main report. Rome. doi: 10.4060/ca9825en

Fearn, T. (2002). Assessing calibrations: SEP, RPD, RER and r2. NIR news, 13(6), 12-13. doi: 10.1255/nirn.689

Fife, D. N., Nambiar, E. K. S., & Saur, E. (2008). Retranslocation of foliar nutrients in evergreen tree species planted in a Mediterranean environment. Tree Physiology, 28(2), 187–196. doi: 10.1093/treephys/28.2.187

Fisher, R. A., & Mackenzie, W. A. (1923). Studies in crop variation. II. The manurial response of different potato varieties. The Journal of Agricultural Science, 13(3), 311–. doi: 10.1017/s0021859600003592

Fox, T. R., Lee Allen, H., Albaugh, T. J., Rubilar, R., & Carlson, C. A. (2007). Tree nutrition and forest fertilization of pine plantations in the southern United States. Southern Journal of Applied Forestry, 31(1), 5-11. doi:10.1093/sjaf/31.1.5

Fujimoto, T., Kobori, H., & Tsuchikawa, S. (2012). Prediction of wood density independently of moisture conditions using near infrared spectroscopy. Journal of Near Infrared Spectroscopy, 20(3), 353-359. doi: 10.1255/jnirs.994

Galvez-Sola, L., García-Sánchez, F., Pérez-Pérez, J. G., Gimeno, V., Navarro, J. M., Moral, R., & Nieves, M. (2015). Rapid estimation of nutritional elements on citrus leaves by near infrared reflectance spectroscopy. Frontiers in Plant Science, 6, 571.

Geladi, P. (2003). Chemometrics in spectroscopy. Part 1. Classical chemometrics. Spectrochimica Acta Part B: Atomic Spectroscopy, 58(5), 767-782.

Geladi, P., & Kowalski, B. R. (1986). An example of 2-block predictive partial least- squares regression with simulated data. Analytica Chimica Acta, 185, 19-32. doi: 10.1016/0003-2670(86)80029-0

González-Pérez, M., Milori, D. M., Colnago, L. A., Martin-Neto, L., & Melo, W. J. (2007). A laser-induced fluorescence spectroscopic study of organic matter in a Brazilian Oxisol under different tillage systems. Geoderma, 138(1-2), 20-24. doi: 10.1016/j.geoderma.2006.10.010

Graciano, C., Goya, J. F., Frangi, J. L., & Guiamet, J. J. (2006). Fertilization with phosphorus increases soil nitrogen absorption in young plants of Eucalyptus grandis. Forest Ecology and Management, 236(2-3), 202-210. doi: 10.1016/j.foreco.2006.09.005

Grant, L. (1987). Diffuse and specular characteristics of leaf reflectance. Remote Sensing of Environment, 22(2), 309-322. doi: 10.1016/0034-4257(87)90064-2

Hardiyanto, E. B., Inail, M. A., & Nambiar, E. K. (2021). Productivity of *Eucalyptus pellita* in Sumatra: *Acacia mangium* legacy, response to phosphorus, and site variables for guiding management. Forests, 12(9), 1186.

Harpole, W. S., Ngai, J. T., Cleland, E. E., Seabloom, E. W., Borer, E. T., Bracken, M. E., Elser, J. J., Gruner, D. S., Hillebrand, H., Shurin, J. B., & Smith, J. E. (2011). Nutrient co-limitation of primary producer communities. Ecology letters, 14(9), 852–862. doi: 10.1111/j.1461-0248.2011.01651.x

Harwood, C. E., Alloysius, D., Pomroy, P., Robson, K. W., & Haines, N. W. (1997). Early growth and survival of *Eucalyptus pellita* provenances in a range of tropical environments, compared with *E. grandis, E. urophylla* and *Acacia mangium*., 14(3), 203–219. doi: 10.1023/a:1006524405455

Hashim, M. N., Hazim, M., & Syafinie, A. M. (2015). Strategic forest plantation establishment in Malaysia for future product development and utilization. International Journal of Agriculture, Forestry and Plantation, 1, 14-24.

Hazelton, P., & Murphy, B. (2016). Interpreting soil test results: What do all the numbers mean? CSIRO publishing.

He, W., & Hu, H. (2013). Rapid prediction of different wood species extractives and lignin content using near infrared spectroscopy. Journal of Wood Chemistry and Technology, 33(1), 52-64. doi: 10.1080/02773813.2012.731463

Hii, S. Y., Ha, K. S., Ngui, M. L., Ak Penguang, S., Duju, A., Teng, X. Y., & Meder, R. (2017). Assessment of plantation-grown *Eucalyptus pellita* in Borneo, Malaysia for solid wood utilisation. Australian Forestry, DOI: 10.1080/00049158.2016.1272526

Hillis, W. E. (1978). Wood quality and Utilization. IN: Hillis, We, Brown, AG (eds.). Eucalyptus for wood production.

Huang, C., Han, L., Yang, Z., & Liu, X. (2009). Ultimate analysis and heating value prediction of straw by near infrared spectroscopy. Waste Management, 29(6), 1793-1797. doi: 10.1016/j.wasman.2008.11.027

Hung, T. D., Brawner, J. T., Meder, R., Lee, D. J., Southerton, S., Thinh, H. H., & Dieters, M. J. (2015). Estimates of genetic parameters for growth and wood properties in *Eucalyptus pellita* F. Muell. to support tree breeding in Vietnam. Annals of Forest Science, 72(2), 205-217. doi: 10.1007/s13595-014-0426-9

Inail, M. A., Hardiyanto, E. B., & Mendham, D. S. (2019). Growth Responses of *Eucalyptus pellita* F. Muell Plantations in South Sumatra to Macronutrient Fertilisers Following Several Rotations of *Acacia mangium* Willd. Forests, 10(12), 1054. doi: 10.3390/f10121054

Jani, H. F. A., Meder, R., Hamid, H. A., Razali, S. M., & Yusoff, K. H. M. (2021). Near infrared spectroscopy of plantation forest soil nutrients in Sabah, Malaysia, and the potential for microsite assessment. Journal of Near Infrared Spectros

Japarudin, Y., Meder, R., Lapammu, M., Alwi, A., Ghaffariyan, M., & Brown, M. (2021). Compression and flexural properties of plantation-grown *Eucalyptus pellita* in Borneo, Malaysia. Potential for structural timber end use. Australian Forestry, 84(3), 139-151. doi: 10.1080/00049158.2021.1962628

Japarudin, Y., Lapammu, M., Alwi, A., Warburton, P., Macdonell, P., Boden, D., Brawner, J., Brown, M., & Meder, R. (2020). Growth performance of selected taxa as candidate species for productive tree plantations in Borneo. Australian Forestry, 83(1), 29–38. doi: 10.1080/00049158.2020.1727181

Johnlee. E. B., Kat, N. K. P., Mohamad, A., Ajik, M., Chong, R., Kimjus, K., & Lapongan, J. (2017) PROCEEDINGS OF THE 18TH MALAYSIAN FORESTRY CONFERENCE “Advancing Sustainable Forestry Through Digitalization and Technology”. 31st July – 2nd August 2018, Kuching, Sarawak. Pg 414-420. http://www.forestry.sarawak.gov.myhttp://www.forestry.sarawak.gov.my

Jolliffe, I. T., & Cadima, J. (2016). Principal component analysis: a review and recent developments. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 374(2065), 20150202. doi: 10.1098/rsta.2015.0202

Kadir, W. R. B. A., Hamzah, A. B., & Sundralingam, P. (1988). Effect of nitrogen and phosphorus on the early growth of three exotic plantation species in Peninsular Malaysia. Journal of Tropical Forest Science, 178-186.

Kiwfo, K., Yeerum, C., Issarangkura Na Ayutthaya, P., Kesonkan, K., Suteerapataranon, S., Panitsupakamol, P., & Grudpan, K. (2021). Sustainable education with local-wisdom based natural reagent for green chemical analysis with a smart device: Experiences in Thailand. Sustainability, 13(20), 11147. doi: 10.3390/su132011147

Kjeldahl, J. (1883). New method for the determination of nitrogen in organic substances. Fresenius Zeitsch Anal Chemie, 22, 366-383.

Kjeldahl, K., & Bro, R. (2010). Some common misunderstandings in chemometrics. Journal of Chemometrics, 24(7-8), 558-564. doi: 10.1002/cem.1346

Krishnapillay, B. (2002). A manual for forest plantation establishment in Malaysia. A manual for forest plantation establishment in Malaysia.

Ludwig, B., Khanna, P. K., Bauhus, J., & Hopmans, P. (2002). Near infrared spectroscopy of forest soils to determine chemical and biological properties related to soil sustainability. Forest Ecology and Management, 171(1-2), 121- 132. doi: 10.1016/s0378-1127(02)00467-x

Ma, T., Schajer, G., Inagaki, T., Pirouz, Z., & Tsuchikawa, S. (2018). Optical characteristics of Douglas fir at various densities, grain directions and thicknesses investigated by near-infrared spatially resolved spectroscopy (NIR- SRS). Holzforschung, 72(9), 789-796.

Ma, T., Tsuchikawa, S., & Inagaki, T. (2021). Wooden material and environmental sciences. In Near-Infrared Spectroscopy (pp. 361-379). Springer, Singapore.

Malaysian Standard MS677. (1980). Recommended Methods for Plant Chemical Analysis: Pt I to IV; Licensed to Agustan Alwi, used only date: 09/03/2020

Malegori, C., Marques, E. J. N., de Freitas, S. T., Pimentel, M. F., Pasquini, C., & Casiraghi, E. (2017). Comparing the analytical performances of Micro-NIR and FT-NIR spectrometers in the evaluation of acerola fruit quality, using PLS and SVM regression algorithms. Talanta, 165, 112-116. doi: 10.1016/j.talanta.2016.12.035

Malley, D. F., Martin, P. D., & Ben-Dor, E. (2004). Application in analysis of soils. Near-infrared spectroscopy in agriculture, 44, 729-784.

Marten, G. C., Halgerson, J. L., & Cherney, J. H. (1983). Quality Prediction of Small Grain Forages by Near Infrared Reflectance Spectroscopy 1. Crop Science, 23(1), 94- 96. doi: 10.2135/cropsci1983.0011183X0023000100

McLellan, T. M., Martin, M. E., Aber, J. D., Melillo, J. M., Nadelhoffer, K. J., & Dewey, B. (1991). Comparison of wet chemistry and near infrared reflectance measurements of carbon-fraction chemistry and nitrogen concentration of forest foliage. Canadian Journal of Forest Research, 21(11), 1689-1693. doi. 10.1139/x91-233

Meder, R., Brawner, J. T., Downes, G. M., & Ebdon, N. (2011). Towards the in-forest assessment of Kraft pulp yield: comparing the performance of laboratory and hand-held instruments and their value in screening breeding trials. Journal of Near Infrared Spectroscopy, 19(5), 421-429. doi: 10.1255/jnirs.954

Meder, R., Gallagher, S., Kimberley, M. O., Uprichard, J. M., & Mackie, K. L. (1994, May). Prediction of wood chip and pulp and paper properties via multivariate analysis of spectral data. In 48th Appita Annual General Conference (pp. 2-6).

Menesatti, P., Antonucci, F., Pallottino, F., Roccuzzo, G., Allegra, M., Stagno, F., & Intrigliolo, F. (2010). Estimation of plant nutritional status by Vis–NIR spectrophotometric analysis on orange leaves [*Citrus sinensis* (L) Osbeck cv Tarocco]. Bbiosystems engineering, 105(4), 448-454. doi: 10.1016/j.biosystemseng.2010.01.003

Minasny, B., McBratney, A. B., Bellon-Maurel, V., Roger, J. M., Gobrecht, A., Ferrand, L., & Joalland, S. (2011). Removing the effect of soil moisture from NIR diffuse reflectance spectra for the prediction of soil organic carbon. Geoderma, 167, 118- 124. doi: 10.1016/j.geoderma.2011.09.008

Moh, F. M. H. (1998). Development of Infrared Spectroscopic Techniques for the Determination of Some Quality Parameters of Palm Oil (Doctoral dissertation, Universiti Putra Malaysia).

Norris, K. H., Barnes, R. F., Moore, J. E., & Shenk, J. S. (1976). Predicting forage quality by infrared reflectance spectroscopy. Journal of Animal Science, 43(4), 889–897. doi: 10.2527/jas1976.434889x

O'Brien, N. A., Hulse, C. A., Friedrich, D. M., Van Milligen, F. J., von Gunten, M. K., Pfeifer, F., & Siesler, H. W. (2012). Miniature near-infrared (NIR) spectrometer engine for handheld applications. In Next-generation spectroscopic technologies V (Vol. 8374, p. 837404). International Society for Optics and Photonics.

Ozaki, Y., Huck, C., Tsuchikawa, S., & Engelsen, S. B. (Eds.). (2021). Near-Infrared Spectroscopy: Theory, Spectral Analysis, Instrumentation, and Applications. Berlin/Heidelberg, Germany: Springer. doi: 10.1007/978-981-15- 8648-4

Pätzold, S., Leenen, M., Frizen, P., Heggemann, T., Wagner, P., & Rodionov, A. (2020). Predicting plant available phosphorus using infrared spectroscopy with consideration for future mobile sensing applications in precision farming. Precision Agriculture, 21(4), 737-761. doi: 10.1007/s11119-019-09693-3

Petisco, C., García-Criado, B., De Aldana, B. V., Zabalgogeazcoa, I., & Mediavilla, S. (2005). Use of near-infrared reflectance spectroscopy in predicting nitrogen, phosphorus and calcium contents in heterogeneous woody plant species. Analytical and Bioanalytical Chemistry, 382(2), 458-465. doi: 10.1007/s00216- 004-3046-7

Petisco, C., García-Criado, B., Vázquez de Aldana, B. R., García-Ciudad, A., & Mediavilla, S. (2008). Ash and mineral contents in leaves of woody species: analysis by near- infrared reflectance spectroscopy. Communications in soil science and plant analysis, 39(5-6), 905-925. doi: 10.1080/00103620701881253

Prananto, J. A., Minasny, B., & Weaver, T. (2021). Rapid and cost-effective nutrient content analysis of cotton leaves using near-infrared spectroscopy (NIRS). PeerJ, 9, e11042. doi: 10.7717/peerj.11042

Ratnasingam, J., Latib, H. A., Paramjothy, N., Liat, L. C., Nadarajah, M., & Ioras, F. (2020). Plantation forestry in Malaysia: An evaluation of its successes and failures since the 1970. Notulae Botanicae Horti Agrobotanici Cluj-Napoca, 48(4), 1789-1801. doi: 10.15835/nbha48412167

Reich, G. (2005). Near-infrared spectroscopy and imaging: basic principles and pharmaceutical applications. Advanced drug delivery reviews, 57(8), 1109-1143. doi: 10.1016/j.addr.2005.01.020

Reuter, D., & Robinson, J. B. (Eds.). (1997). Plant analysis: an interpretation manual. CSIRO publishing.

Richardson, A. D., Reeves III, J. B., & Gregoire, T. G. (2004). Multivariate analyses of visible/near infrared (VIS/NIR) absorbance spectra reveal underlying spectral differences among dried, ground conifer needle samples from different growth environments. New Phytologist, 161(1), 291-301. doi: 10.1046/j.1469- 8137.2003.00913.x

Rinnan, Å., Nørgaard, L., van den Berg, F., Thygesen, J., Bro, R., & Engelsen, S. B. (2009). Data pre-processing. Infrared spectroscopy for food quality analysis and control, 29-50.

Roberts, J., & Cozzolino, D. (2017). Wet or dry? The challenges of NIR to analyse soil samples. NIR News, 28(4), 3–5. doi: 10.1177/0960336017707884

Sabah Forestry Department. Undated. History of plantation forestry in Sabah. [accessed 2020 Jan 11]. Available from: http://www.forest.sabah.gov.my/pdf/520ForestPlantationhistory.pdf

Sankaran, K. V., Chacko, K. C., Pandalai, R. C., Kumaraswamy, S., O'Connell, A. M., Grovez, T. S., & Mendhamz, D. S. (2004). Improved Productivity of Eucalypt Plantations through Site Management Practices in. In Site Management and Productivity in Tropical Plantation Forests: Proceedings of Workshops in Congo, July 2001 and China, February 2003 (p. 61). CIFOR.

Santos, A. J., Alves, A. M., Simões, R. M., Pereira, H., Rodrigues, J., & Schwanninger, M. (2012). Estimation of wood basic density of *Acacia melanoxylon* (R. Br.) by near infrared spectroscopy. Journal of Near Infrared Spectroscopy, 20(2), 267-274.

Savitzky, A., & Golay, M. J. (1964). Smoothing and differentiation of data by simplified least squares procedures. Analytical chemistry, 36(8), 1627-1639. doi: 10.1021/ac60214a047

Schimleck, L. R., Raymond, C. A., Beadle, C. L., Downes, G. M., Kube, P. D., & French, J. (2000). Applications of NIR spectroscopy to forest research. Appita Journal, 53(6), 458-464.

Schimleck, L. R., Matos, J. L. M., Trianoski, R., & Prata, J. G. (2018). Comparison of methods for estimating mechanical properties of wood by NIR spectroscopy. Journal of Spectroscopy, 2018, 1–10. doi: 10.1155/2018/4823285

Schönau, A. P. G., & Coetzee, J. (1989). Initial spacing, stand density and thinning in eucalypt plantations. Forest ecology and management, 29(4), 245–266. doi: 10.1016/0378-1127(89)90097-2

Selvaraj, P., & Muhammad, A. B. (1980). A checklist of plantation trials in Peninsular Malaysia. A checklist of plantation trials in Peninsular Malaysia. (79).

Shenk, J. S., Westerhaus, M. O., & Hoover, M. R. (1979). Analysis of forages by infrared reflectance. Journal of. Dairy Science, 62, 807–812.

Shenk, J. S., Westerhaus, M. O., & Templeton Jr, W. C. (1985). Calibration transfer between near infrared reflectance spectrophotometers 1. Crop science, 25(1), 159-161. doi:10.2135/cropsci1985.0011183X002500010

Sims, D. A., & Gamon, J. A. (2002). Relationships between leaf pigment content and spectral reflectance across a wide range of species, leaf structures and developmental stages. Remote sensing of environment, 81(2-3), 337-354. doi: 10.1016/s0034-4257(02)00010-x

Sinnaeve, G., Dardenne, P., Agneessens, R., & Biston, R. (1994). The use of near infrared spectroscopy for the analysis of fresh grass silage. Journal of Near Infrared Spectroscopy, 2(1), 79 - 84. doi: 10.1255/jnirs.34

Sjostrom, E. (1993). Wood chemistry: fundamentals and applications. Gulf professional publishing.

Smethurst, P., Holz, G., Moroni, M., & Baillie, C. (2004). Nitrogen management in *Eucalyptus nitens* plantations. Forest Ecology and Management, 193(1- 2), 63-80. doi: 10.1016/j.foreco.2004.01.023

Spohn, M., & Kuzyakov, Y. (2013). Phosphorus mineralization can be driven by microbial need for carbon. Soil Biology and Biochemistry, 61, 69–75. doi: 10.1016/j.soilbio.2013.02.013

Sun, D., Dickinson, G. R., & Robson, K. J. (1996) Growth of *Eucalyptus pellita* and *E. urophylla* and effects on pasture production on the coastal lowlands of tropical northern Australia., Australian Forestry, 59:3, 136-141, doi: 10.1080/00049158.1996.10674679.

Tarigan, M., Roux, J., Wingfield, M. J., Van Wyk, M., & Tjahjono, B. (2010). Three new Ceratocystis spp. in the Ceratocystis moniliformis complex from wounds on *Acacia mangium* and *A. crassicarpa*. Mycoscience, 51(1), 53-67. doi: 10.1007/s10267- 009-0003-5

Tsuchikawa, S. (2007). A Review of Recent Near Infrared Research for Wood and Paper, Applied Spectroscopy Reviews, 42:1, 43-71. doi: 10.1080/05704920601036707

Tsuchikawa, S., Inoue, K., Noma, J., & Hayashi, K. (2003). Application of near-infrared spectroscopy to wood discrimination. Journal of Wood Science, 49:29–35.

Tyson, J. A., Schimleck, L. R., Aguiar, A. M., Abad, J. I. M., Rezende, G. D., & Otávio Filho, M. (2012). Development of near infrared calibrations for physical and mechanical properties of eucalypt pulps of mill-line origin. Journal of Near Infrared Spectroscopy, 20(2), 287-294. doi: 10.1255/jnirs.988

Üner, B., Karaman, İ., Tanrıverdi, H., & Özdemir, D. (2011). Determination of lignin and extractive content of Turkish Pine (*Pinus brutia* Ten.) trees using near infrared spectroscopy and multivariate calibration. Wood science and technology, 45(1), 121-134. doi: 10.1007/s00226-010-0312- z

van Maarschalkerweerd, M., Bro, R., Egebo, M., & Husted, S. (2013). Diagnosing latent copper deficiency in intact barley leaves (*Hordeum vulgare*, L.) using near infrared spectroscopy. Journal of Agricultural and Food Chemistry, 61(46), 10901- 10910. doi: 10.1021/jf402166g

Viera, M., Ruíz Fernández, F., & Rodríguez-Soalleiro, R. (2016). Nutritional prescriptions for Eucalyptus plantations: lessons learned from Spain. Forests, 7(4), 84. doi: 10.3390/f7040084

Villatoro-Pulido, M., Moreno Rojas, R., Muñoz-Serrano, A., Cardeñosa, V., Amaro López, M. Á., Font, R., & Del Río-Celestino, M. (2012). Characterization and prediction by near- infrared reflectance of mineral composition of rocket (*Eruca vesicaria* subsp. *sativa* and *Eruca vesicaria* subsp. *vesicaria*). Journal of the Science of Food and Agriculture, 92(7), 1331- 1340. doi: 10.1002/jsfa.4694

Walkley, A., & Black, I. A. (1934). An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Science, 37, 29-38.

Wallbäcks, L., Edlund, U., Norden, B., & Berglund, I. (1991). Multivariate characterization of pulp using solid-state 13C NMR, FTIR, and NIR. Tappi Journal (USA).

Warburton, P., Brawner, J., & Meder, R. (2014). Handheld near infared spectroscopy for the prediction of Leaf physiological status in tree seedlings. Journal of Near Infrared Spectroscopy, 22(6), 433-438. doi: 10.1255/jnirs.1137

Ward, A., Nielsen, A. L., & Møller, H. (2011). Rapid assessment of mineral concentration in meadow grasses by near infrared reflectance spectroscopy. Sensors, 11(5), 4830-4839. doi: 10.3390/s110504830

West, P. W. (2014). Growing plantation forests. Springer-Verlag, 83-98. doi: 10.1007/978- 3-319-01827-0

Williams, P. (2019). Karl H. Norris, the father of near-infrared spectroscopy. NIR news, 30(7-8), 25-27. doi: 10.1177/0960336019875883

Williams, P. C. (2001). Implementation of Near-Infrared Technology the Agricultural and Food Industries, 2nd Edition, American Association of Cereal Chemists, St. Paul, 145-169.

Williams, P. C., & Sobering, D. C. (1993). Comparison of commercial near infrared transmittance and reflectance instruments for analysis of whole grains and seeds. Journal of Near Infrared Spectroscopy, 1(1), 25-32. doi: 10.1255/jnirs.3

Williams, P. (2010). Tutorial: The RPD statistic: a tutorial note. NIR news, 21(1), 22–26. doi: 10.1255/nirn.1419

Wold, S., Geladi, P., Esbensen, K., & Öhman, J. (1987). Multi-way principal components- and PLS-analysis. Journal of Chemometrics, 1(1), 41-56. doi: 10.1002/cem.1180010107

Wold, S., Trygg, J., Berglund, A., & Antti, H. (2001). Some recent developments in PLS modeling. Chemometrics and intelligent laboratory systems, 58(2), 131-150. doi: 10.1016/s0169-7439(01)00156-3

Wright, J. A., Birkett, M. D., & Gambino, M. J. T. (1990). Prediction of pulp yield and cellulose content from wood samples using near infrared reflectance spectroscopy. Tappi Journal, 73(8), 164-166.

Xu, D., Dell, B., Malajczuk, N., & Gong, M. (2002). Effects of P fertilisation on productivity and nutrient accumulation in a *Eucalyptus grandis* × *E. urophylla* plantation in southern China. Forest Ecology and Management, 161(1- 3), 0–100. doi: 10.1016/s0378-1127(01)00485-6

Yang, Z., Liu, Y. N., Lv, B., & Xie, X. Q. (2012). Rapid Classification of Softwood and Hardwood by Near Infrared Spectroscopy of Wood Tangential Section. In Applied Mechanics and Materials (Vol. 157, pp. 1624-1627). Trans Tech Publications Ltd. doi: 10.4028/www.scientific.net/AMM.157-158.1624

Zhai, Y., Cui, L., Zhou, X., Gao, Y., Fei, T., & Gao, W. (2013). Estimation of nitrogen, phosphorus, and potassium contents in the leaves of different plants using laboratory-based visible and near-infrared reflectance spectroscopy: comparison of partial least-square regression and support vector machine regression methods. International Journal of Remote Sensing, 34(7), 2502-2518. doi: 10.1080/01431161.2012.746484

Ziegel, E. R. (2004). A user-friendly guide to multivariate calibration and classification. doi: 10.1198/004017004000000167