QUANTIFYING OF SOIL ORGANIC CARBON AND TOTAL NITROGEN THROUGH NEAR INFRARED SPECTROSCOPY ON FOREST PLANTATIONS IN SABAH, MALAYSIA

By

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Chair : **Professor Hazandy bin Abdul Hamid, PhD**
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Understanding the physiochemical properties of soil is critical in ensuring the optimal growth of crops and trees in forest plantation. The utility of near infrared (NIR) spectroscopy has proven as an effective and inexpensive method for soil properties evaluation. Nevertheless, it requires a calibrated technique that must be developed to account for the heterogeneity of specific regions. Thus, this study aimed to develop NIR spectral calibrations for quantitation of soil total organic carbon (TOC) and total nitrogen (TN). Soil samples were collected from three sites in Sabah, Malaysia, namely Pitas, Kota Marudu, and Tawau districts. Soil TOC and TN were obtained from 143 soil samples that were collected, scanned, and analysed using standard chemical method and NIR spectroscopy. Partial least squares regression (PLSR) analysis using cross validation was performed and then validated using independent sample set. Calibrations were generated utilising only the A-horizon samples due to inadequate sampling size to be used as an independent validation set. The predictions of TOC and TN concentrations by the PLSR method were statistically sound, with high coefficients of determination for the validation set (R^2_{pred} TOC =0.77 and R^2_{pred} TN =0.53) and low root mean square error of prediction ($RMSEP_{TOC}$ =0.44 and $RMSEP_{TN}$ =0.051). The implementation of these calibrations to offer spatial evaluation of two contrasting micro-sites within a same area (AFI site) was also demonstrated. The study also demonstrates the potential utility of NIR spectroscopy predictions in swiftly and non-invasively characterizing site-soil attributes, thereby presenting it as an important decision support tool in managing forest plantations, particularly when combined with NIR spectroscopic measurement of foliar nutrient levels.

Keywords: soil nutrition, soil organic carbon, total nitrogen, pH, near infrared spectroscopy, NIR

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

PENGUKURAN KANDUNGAN KARBON ORGANIK DAN JUMLAH NITROGEN TANAH MELALUI KAEDAH SPEKTROSKOPI SINARAN INFRAMERAH DI LADANG PERHUTANAN DI SABAH, MALAYSIA

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Pengetahuan tentang ciri fizikal dan kimia tanah adalah sangat penting untuk memastikan pertumbuhan optimal tanaman dan pokok dalam penanaman hutan perladangan. Keberkesanan spektroskopi *Near Infrared (NIR)* telah terbukti sebagai kaedah yang berkesan dan berkos rendah untuk penilaian pelbagai ciri-ciri tanah. Namun begitu, kaedah ini perlu dibangunkan dengan menggunakan teknik kalibrasi yang mengambil kira kepelbagaian dalam sesebuah kawasan. Oleh itu, kajian ini bertujuan untuk membangunkan penentukuran kalibrasi spektra NIR untuk kuantifikasi kandungan jumlah karbon organik (TOC) dan kandungan jumlah nitrogen (TN) dalam tanah. Sampel tanah telah diambil dari daerah Pitas, Kota Marudu dan Tawau di Sabah, Malaysia. Sejumlah 143 sampel tanah telah diambil, diimbas, dan dianalisis menggunakan kaedah piawaian kimia dan kaedah *NIR spectroscopy*. Regresi Kuasa Dua Terkecil Separa dengan pengesahan silang telah digunakan bagi membangunkan penentukuran di antara data rujukan dan imbasan NIR dan data yang telah disahkan menggunakan set sampel bebas. Hasil penentuan TOC dan TN yang didapati adalah baik secara statisitik, dengan pekali penentuan yang tinggi untuk set pengesahan (R^2_{pred} TOC =0.77 and R^2_{pred} TN =0.53) dan ($RMSEP_{TOC}$ =0.44 and $RMSEP_{TN}$ =0.051) untuk keputusan ralat ramalan punca kuasa dua rendah. Selain itu, hasil kalibrasi juga telah digunapakai untuk penilaian spatial di dua tempat kecil dalam satu kawasan yang sama (tapak kajian AFI). Kajian ini telah menunjukkan kebolehan spekroskopi NIR dalam mendapatkan maklumat tanah secara pantas dan tanpa merosakkan kawasan serta menjadi sebuah alat sokongan penting dalam dalam pengurusan perladangan hutan.

Kata Kunci: nutrien tanah, jumlah karbon organik, jumlah nitrogen, pH, spektrosokopi *Near-Infrared*, *Near infrared*

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

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LIST OF ABBREVIATIONS

AFC	Asian Forestry Company (Sabah)
AFI	Acacia Forest Industries
BFC	Borneo Forestry Cooperative
NIR	Near Infrared
NMR	Nuclear Magnetic Resonance
mid-IR	Mid-Infrared
FTIR/FT-IR	Fourier-Transform Infrared
SOC	Soil Organic Carbon
TN	Total Nitrogen
N	Nitrogen
pH	Potential of Hydrogen
LVF	Linear Variable Filter
PCA	Principal Component Analysis
PLS	Partial Least Squares
R^2	Coefficient of Determination
RMSE	Root Mean Square Error
RMSEC	Root Mean Square Error Calibration
RMSEP	Root Mean Square Error Prediction
MSC	Multiplicative Scatter Correction
SNV	Standard Normal Variate
SSB	Sabah Softwoods Berhad

CHAPTER 1

INTRODUCTION

1.1 Background of Research

Soil fertility is measured in terms of the soil's fundamental capability to provide necessary nutrients for plants in sufficient quantities in order to achieve optimal crop production, together with optimum financial advantage and minimal destruction of the environment (Chakraboty and Mistri, 2015). Physical and chemical soil studies, foliar analysis, and visual observation of plant nutrient deficiency symptoms can all be used to measure soil fertility (Dalal and Rao, 2017). Understanding the soil quality is highly essential in establishing an agricultural site including forest tree and oil palm plantations. In commercial forest plantations, fertilizer is frequently used to boost the growth and robustness of new trees (Gonçalves et al., 2008; Alwi et al., 2020). Depending on the soil conditions, the addition of nitrogen and phosphorus is a customary practice, as well as other macro- and micronutrients. For tree plantations, it is essential to evaluate the soil's nutritional state and monitor the tree’s growth over a certain rotation period in order to maximize the fertilizer application rate.

Malaysia is characterized by a wide variety of soil types that have developed over different topographic conditions, different parent materials or rock types, and alluvial deposits (Sung et al., 2017). Such variability necessitates soil sampling and analysis on a large scale in the laboratory, often at a significant expense and long processing time. Furthermore, given the inherent within-site variability, there is a pressing need for timely and non-destructive approaches of examination. Although near-infrared (NIR) spectroscopy has been demonstrated to be an effective method for swift and inexpensive soil evaluation, its application in tree plantations has been fairly sluggish. This trend was highlighted by Meder et al. (2007) in spectral analyses from nuclear magnetic resonance (NMR), near-infrared (NIR), and mid-IR spectroscopy focusing on a linear transect of land-use systems encompassing native forest, cleared pasture, and re-forested pasture.

Viscarra-Rossel et al. (2016) indicated that the application of near infrared spectroscopy had found success in the forestry and timber products industries for predicting wood quality. However, the integration of soil NIR spectroscopy analysis has been established since 1986 (Dalal and Henry, 1986). Despite the historical precedence, there is still a long way to go before NIR spectroscopy is widely accepted in the forestry sector as a standard analytical tool (Meder and

Schimleck, 2011; Meder and Tsuchikawa, 2011). Over the years, researchers have developed global NIR calibration models for soil organic carbon (SOC), such as the work done by Viscarra-Rossel et al. (2006), with varying degrees of success. In spite of the fact that global models have an extensive range of applications, they are frequently inaccurate due to their inability to account for soil variations on a local scale. Currently, the only quantitative spectral analysis done on Malaysian soil remains limited to the study conducted by Gholizadeh et al. (2014), who focused on developing calibration for soil physical properties in the paddy field using Vis-NIR and NIRS. Therefore, there is significant importance in developing calibrations to account for local soil, especially in Sabah, to improve the accuracy of soil property predictions, which can lead to better decision-making in areas such as agriculture, forestry, and environmental management.

Accordingly, the research was undertaken to examine a rapid and cost-effective alternative for soil characterization of total organic carbon, total nitrogen, and pH using a handheld NIR spectroscopy on soil samples collected from three sites in Sabah, namely Pitas, Kota Marudu, and Tawau. There is a promising potential integrating this method with foliar nitrogen and phosphorus monitoring using the same portable NIR spectrometer to provide forest growers with a decision support tool (Lee et al., 2015).

1.2 Objectives

The purpose of this research was to develop an NIR spectral calibrations for quantitation of soil total organic carbon (TOC) and total nitrogen (TN) in three sites in Sabah, Malaysia, namely Pitas, Kota Marudu, and Tawau. The specific objective of this research was to calibrate and validate spectral data of dry-ground soil samples with SOC and TN chemical data using partial least squares regression. This is specifically undertaken via the following steps:

1. Calibrate and validate a NIR spectral calibration model for the three sites in Sabah for soil total organic carbon (TOC) and total nitrogen (TN) content via partial least squares regression of NIR spectra and corresponding reference values of TOC and TN from conventional laboratory analysis.
2. Demonstrate the capability of NIR spectroscopy in estimating soil total organic carbon and total nitrogen content at high spatial resolution in two sites in AFI Pitas, Sabah.

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