Author(s): Hein, Paulo R. G.; Pakkanen, Hannu; Santos, António A. Dos

Title: Challenges in the use of Near Infrared Spectroscopy for improving wood quality : A review

Year: 2017

Version:

Please cite the original version:

Hein, P. R. G., Pakkanen, H., & Santos, A. A. D. (2017). Challenges in the use of Near Infrared Spectroscopy for improving wood quality : A review. Forest Systems, 26(3), eR03. https://doi.org/10.5424/fs/2017263-11892

Forest Systems
26 (3), eR03, 10 pages (2017)
eISSN: 2171-9845
https://doi.org/10.5424/fs/2017263-11892
Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria O. A., M. P. (INIA)

REVIEW ARTICLE

OPEN ACCESS

Challenges in the use of Near Infrared Spectroscopy for improving wood quality: A review

Paulo R. G. Hein[1], Hannu K. Pakkanen[2], and António A. Dos Santos[3]

[1] *Federal University of Lavras, Dept. of Forest Science, Lavras, CP37, 37200-000, Brazil* [2] *University of Jyvaskyla, Dept. of Chemistry, Jyvaskyla, PO Box 35, FI-40014, Finland* [3] *University of Lisbon, Forest Research Center, Lisbon 1349-017, Portugal*

Abstract

Aims of study: Forestry-related companies require quality monitoring methods capable to pass a large number of samples. This review paper is dealing with the utilization of near infrared (NIR) technique for wood analysis.

Area of study: We have a global point of view for NIR applications and characterization of different kind of wood species is considered.

Material and methods: NIR spectroscopy is a fast, non-destructive technique, applicable to any biological material, demanding little or no sample preparation. NIR spectroscopy and multivariate analysis serve well in laboratories where the conditions are controlled. The main challenges to NIR spectroscopy technique in field conditions are moisture content and portability.

Results: In this review, the methods and challenges for successfully applying NIR spectroscopy in the field of wood characterization are presented. Portable equipment need to record NIR spectra with low noise and low sensitivity to temperature and humidity variations of the air in forest environments. Studies concerning the sample preparation effects on the robustness of the calibrations are thus required.

Research highlights: This paper examines traditional applications and practical aspects as well as innovative modern adaptations applied, for example, in hyperspectral imaging and genetic studies.

Additional keywords: Near Infrared Spectroscopy; wood properties; moisture; pulp; camera hyperspectral, genetic studies.

Abbreviations used: MC (moisture content); PCR (principal component regression); PLS (least squares regression); R^2 (coefficient of determination); RMSECV (root mean square error of cross validation); r^2p (determination coefficient in test set validation); RDP (ratio of performance to deviation); UV (ultraviolet); S/G (syringyl to guaiacyl ratio).

Authors´ contributions: PRGH elaborated the first draft of the manuscript; HKP and AAS critical reviewed the manuscript. All authors wrote and approved the final manuscript.

Citation: Hein, P. R. G.; Pakkanen, H. K.; Dos Santos, A. A. (2017). Challenges in the use of Near Infrared Spectroscopy for improving wood quality: A review. Forest Systems, Volume 26, Issue 3, eR03. https://doi.org/10.5424/fs/2017263-11892

Received: 14 Jun 2017 **Accepted:** 12 Dec 2017

Funding: CNPq (process 405085/2016-8); FAPEMIG (process APQ-00509-14).

Competing interests: The authors have declared that no competing interests exist.

Correspondence should be addressed to Paulo R. G. Hein: paulo.hein@dcf.ufla.br

Introduction

A challenge for tree breeders and wood quality researchers of today is to respond appropriately to a complex environment demanding more productivity, higher quality, and a quicker adaptation of their crops to rapid changes (Verryn, 2008). In this context, it is essential to know the variability, inheritance, as well as genetic and environmental control of the wood traits and the implications of these with other properties (Raymond, 2002). Hence the use of new available techniques can make a significant contribution to understand how and why wood properties change along tree stems (Pereira *et al.*, 2016).

In order to accurately measure the wood traits, there is the need to have systems capable of evaluating the wood properties rapidly, precisely, and at low cost without altering the end-use potential of the wood material. Among the current techniques, Near Infrared (NIR) spectroscopy has come of age and is now prominent among major analytical technologies after the NIR region was discovered in 1800, revived and developed in the early 1950s and put into practice in the 1970s (Manley, 2014).

NIR spectroscopy is a fast, non-destructive technique (measuring time: 1 min or less) applicable to any biological material, including on-line processes, demanding little or no sample preparation (Pasquini, 2003). It is based on vibrational spectroscopy that measures the interaction between light and the material (Næs *et al.*, 2002). Bokobza (1998) and Pasquini (2003) extensively reviewed the basic theory of NIR spectroscopy and its applications presenting the concepts that make a NIR spectrum understandable.

In this review, the main challenges for successfully applying NIR spectroscopy in wood are presented. A range of studies dealing with moisture content and portability of NIR devices are examined and the use of NIR-based models in hyperspectral imaging and genetic studies are discussed.

Near infrared spectroscopy in forest sector

NIR spectroscopy has been appointed as an emerging technology that could provide large data set of wood measurements helping to understand how genetic and environmental factors induce variation in woods (So *et al.*, 2004). As pointed out by Meder *et al.* (2011), after a considerable effort in the last two decades, NIR spectroscopy has been accepted as a tool to provide either local or global models for the prediction of many wood traits in softwood and hardwood trees. NIR spectroscopy models are especially attractive for tree breeders and genetic programs because it is possible to quickly provide estimates of many wood traits from a single NIR spectrum, if a NIR-based calibration is available (Santos *et al.*, 2015). Since measuring NIR spectra is a simple operation, large data set can be rapidly produced at relatively low cost.

NIR spectroscopy with aid of multivariate statistics and computational systems is useful for quantitative but even more for qualitative applications, including classification of wood and other biological materials (Tsuchikawa & Kobori, 2015). In summary, the technique relies on developing a calibration that relates the NIR spectra of a large number of wood samples to their known chemical constitution, for example pulp yield or cellulose content (Raymond, 2002). This NIR-based calibration is then used to predict, for instance, the pulp yield or cellulose content of further samples. In addition to the chemical composition, the physical (Cogdill *et al.*, 2004), mechanical (Kelley *et al.*, 2004) properties could also be predicted using NIR spectroscopy.

For qualitative analysis, the main multivariate technique is Principal Component Analysis (PCA) and Partial Least Squares Discriminant Analysis (PLS-DA) while for quantitative studies, the most common techniques for calibrating a predictive model are Principal Component (PC) and Partial Least Squares (PLS) regressions (Næs *et al.*, 2002).

Wood characterization

The first works that used the NIR spectroscopy technique to characterize wood concentrated on properties directly related to wood chemistry and were based on milled chips obtained from composite whole-tree samples. Birkett & Gambino (1989), Easty *et al.* (1990), Wright *et al.* (1990) and Wallbäcks *et al.* (1991) presented the first results concerning NIR spectra and chemical properties of the wood, especially its cellulose content.

Later, NIR spectroscopy approach has been also extended to assess non-chemical characteristics of solid wood samples showing that NIR technology is capable to also estimate physical, mechanical, and anatomical features. Tsuchikawa *et al.* (1992) have investigated the effect of the surface-structure of wood on NIR spectroscopy. The first study involving NIR spectra and wood density was probably presented by Thygesen (1994). She used Norway spruce (*Picea abies* (L.) Karst.) shavings and solid wood for demonstrating that the technique could be used to estimate the dry matter content and density of wood. Afterward, NIR spectroscopy was applied by Hoffmeyer & Pedersen (1995) for solid wood samples of the same species to evaluate dry density (dry weight per dry volume). They stated that NIR spectroscopy could be used to predict wood density as well as compression and bending strength of dry wood. Santos *et al.* (2012) also estimated wood basic density of Australian Blackwood (*Acacia melanoxylon*) using NIR spectroscopy. It was also concluded that at least 45 samples for calibration and a further 16 samples for validation are necessary to obtain acceptable models for screening.

Moisture content

Wood, like many natural materials, is hygroscopic; it takes on moisture from the surrounding environment. Moisture content (MC) exchange between wood and air depends on the relative humidity and temperature of the air and the current amount of water in the wood (Glass & Zelinka, 2010). The moisture variation has an important influence on wood properties and performance, affecting strength, drying, processing, glue curing, and bond performance (Adedipe & Dawson-Andoh, 2008). As pointed out by Leblon *et al.* (2013), wood industry has particular interest for models capable of handling a broader range of moisture content variations in order to be able to measure MC at different steps of the manufacturing process, whatever the level of MC. Thus, many studies have been developed to deal with this important issue.

Hoffmeyer & Pedersen (1995) have reported NIR calibrations for MC below 30% of Norway spruce (*Picea abies*) wood samples with R^2 of 0.99 and standard error of predictions lower than 0.50%.

Thygesen & Lundqvist (2000) have investigated the effect of peak shifts in NIR spectra of moist wood samples due to temperature variations in NIR calibrations for moisture. They used different strategies to deal with this problem. These model approaches yielded good prediction errors (8–10%) for MC of unknown samples.

Defo *et al.* (2007) have reported NIR calibrations for predicting MC of solid red oak (*Quercus* spp.) wood taking into account the effect of grain orientation. They obtained good predictions using NIR spectra collected from transverse or radial surfaces between 1000 and 2300 nm, with root mean square of errors of prediction of less than 3.6%.

Adedipe & Dawson-Andoh (2008) have examined the feasibility of using NIR spectra for estimating MC of yellow-poplar (*Liriodendron tulipifera*) veneer sheets. According to their results, both principal component regression (PCR) and partial least squares regression (PLS) models for estimating MC presented correlations $R^2 > 0.94$. When they used only the spectra window from 1400 to 1900 nm (a region between the two main hydroxyl absorption peaks) the correlation coefficients R^2 were 0.985 and 0.986 for PCR and PLS, respectively.

Watanabe *et al.* (2010) showed that surface MC of western hemlock (*Tsuga heterophylla*) varying from 5 to 105% can be predicted in real time at relatively rapid line speed (up to 1 m/s) by using a single NIR spectrum for robust and flexible monitoring of MC in wood. Watanabe *et al.* (2011) also calibrated a NIR-based model for MC of western hemlock wood samples belonging to three moisture classes. NIR spectroscopy showed good ability for predicting MC of the three moisture groups while the commercial capacitance-type moisture meter failed to establish a significant difference between middle- and high-moisture groups.

Mora *et al.* (2011a) applied NIR spectroscopy for the estimation of MC of loblolly pine (*Pinus taeda*) wood. They recorded NIR spectra from the transverse surface of the green discs and developed calibrations model for MC with $R^2 = 0.85$ and mean square errors of 2.1%.

Cooper *et al.* (2011) developed NIR-based models for estimating MC of southern pine (*Pinus sp.*), western redcedar (*Thuja plicata*) and Pacific silver fir (*Abies amabilis*). They reported that it was possible to estimate average MC within ±10–30% of measured value of air-dried wood samples by NIRS at high moisture contents and more accurately (±2–5%) below 30% MC. They showed MC predictions for conditioned samples within 2–3% of measured values in the 0–30% MC range.

Hans *et al.* (2012) applied NIR spectroscopy for estimating MC of frozen and unfrozen black spruce logs. They acquired spectra on sapwood and heartwood as well on tangential and transversal log sections and developed predictive models for the frozen and unfrozen logs separately (temperature-specific models) and for both kinds of logs together (generalized model). Both model types gave similar prediction accuracy and there were no temperature condition effects on the NIR-based calibrations for MC estimations.

Haddadi *et al.* (2016) calculated the absorption and scattering coefficients, transport absorption and the penetration depth from visible–near infrared reflectance spectra acquired over thin samples of quaking aspen (*Populus tremuloides* Michx.) and black spruce (*Picea mariana* Mill.) conditioned at three different moisture levels (3, 7 and 16%). The best PLS model for MC of black spruce, quaking aspen and both species presented a root mean square error of cross validation (RMSECV) of 1.40%, 1.09% and 1.23%, respectively and the coefficient of determination (R^2cv) was higher than 0.94. For black spruce and quaking aspen samples, the penetration depth reaches its maximum (around 1.3 mm) between 800 nm and 1300 nm, but beyond 1300 nm it decreases and reaches only 0.2 mm above 1450 nm.

Application reviews and spectra interpretation of wood components

NIR spectroscopy has been widely used to evaluate many wood traits covering a wide range of applications. Many review articles describing a range of applications of NIR spectroscopy in the forest and wood researches are available. Schimleck *et al.* (2000), So *et al.* (2004), Tsuchikawa (2007), Tsuchikawa & Schwanninger (2013) and Tsuchikawa & Kobori (2015) presented complete review papers on NIR spectroscopy applications in wood research where recent technical and scientific reports have been widely presented and discussed. Leblon *et al.* (2013) listed the researches on NIR spectroscopy for real-time monitoring specifically moisture content and wood density. In regard to the NIR spectra and regression coefficients interpretations, a complete discussion about the band assignments for wood and wood components has been presented by Schwanninger *et al.* (2011). They have compiled detailed tables comprising band locations in wavenumber, the component likely to absorb at this band location, the bond vibration, as well as descriptive remarks. Sandak J *et al.* (2016) published a tutorial for use of NIR spectroscopy in wood and its products based on more than 40 years of collective experience and summarized cutting-edge knowledge in instrumentation, spectral acquisition and data mining in relation to the wood science and technology. They provide practical recommendations and inform young scientists the critical steps in using NIR spectroscopy to assess wood quality while alert managers to the level of operator skill required for the successful adoption of NIR technology.

In short, many research teams have been dedicated to the NIR applications on wood and its products, among which we like to highlight the following leading teams: Saturo Tsuchikawa (Japan), Manfred Schwanninger – *in memoriam* (Austria), Laurence Schimleck (USA), José Carlos Rodrigues (Portugal), Gilles Chaix (France), Anna and Jakub Sandak (Italy), Brian Via (USA) and Roger Meder (Australia).

Practical aspects in wood NIR measurements

Laboratory *vs.* portable NIR devices

Portable NIR systems offer a low-cost alternative to laboratory systems. According to Meder *et al.* (2011) the sample presentation options, wavelength range and resolution of these devices are reduced, but suitable calibrations can be established. Thus, portable instruments can help the acceptance of NIR technology as a reliable tool for characterizing wood. Portability also realizes the ultimate goal of delivering a device that can be taken into the forest and applied to assess individual standing trees, enabling non-destructive evaluation of every individual tree in a breeding trial.

Downes *et al.* (2010) developed NIR calibrations to estimate Kraft pulp yield and cellulose content from NIR spectra taken breast height strips of *Eucalyptus nitens* trees. They compared calibrations developed from NIR spectra recorded using laboratory and portable instruments and found out that both devices were effective in predicting radial variation, with standard errors of prediction of 1%.

Meder *et al.* (2011) compared the performance of a laboratory-based full-range Fourier transform NIR system with two portable NIR devices operating at two different spectral ranges. Calibrations for Kraft pulp yield and cellulose content were developed for the laboratory NIR and a range of hand-held portable NIR instruments. Their study demonstrated that the wavelength range and resolution of the portable instruments are adequate showing promising results and pointing out that the properties (wavelength range and resolution) of the portable instruments are suitable for the prediction of Kraft pulp yield and cellulose content.

Hans *et al.* (2012) tested a hand-held micro-electro-mechanical system (MEMS) based on NIR spectrometer to estimate moisture content and basic specific gravity of frozen and unfrozen black spruce logs. They stated that this type of spectrometer apparatus can be used independently of temperature and freezing conditions.

Sandak A *et al.* (2016) reported their initial experiences of comparing a laboratory-grade instrument (MPA, Bruker Optics GmbH, Ettlingen, Germany) and portable NIR device (MicroNIR 1700, Viavi Solutions, Santa Monica, CA, USA) for detecting wood defects such as reaction wood, knots, resin pockets, discoloration due to fungal attack, stain and decay.

They also successfully tested calibration transfer of chemometric models between laboratory and in-field instruments. Their findings clearly demonstrated that both instruments may be used for detection of wood defects (abnormal wood) and for their classification (knot, resin pocket and compression wood), although further studies are required for ensuring sufficient reliability of models, compensating variability in the conditions during measurement.

Accuracy of NIR technology for predicting wood properties in laboratory conditions

The reliability of the NIR predictions can be verified by validation of models (Brereton, 2003). The best way to test a calibration model, whether it is a quantitative or a qualitative model, is to have some samples in reserve, that are not included among the ones on which the calibration calculations are based, and use those samples as validation samples, sometimes called *test* or *prediction samples* (Mark & Workman, 2007). In regard to the validation of the NIR-based models for wood properties, several studies have used independent test sets to validate their NIR-based calibration for wood traits (Rodrigues *et al.*, 2006; Sousa-Correia *et al.*, 2007; Hein *et al.*, 2009).

Rodrigues *et al.* (2006) presented an interesting paper where they demonstrated that predicted values can be better than expected from cross-validation results using Klason lignin content estimations in wood meal samples of 15-year-old maritime pine (*Pinus pinaster*). They developed calibration for lignin content, but due to low precision and accuracy in the reference data set, NIR-based regression yielded a slope of 0.51 and an intercept at 14% lignin. Then, they expressed with an independent data set for external validation, obtained with higher precision and accuracy, that the NIR PLS-R model based on the noisy reference data led to better results: the slope of the correlation between predicted and reference values was 0.89 and the intercept was 3.9% of lignin. Thus, these findings demonstrated that the model performed much better than expected from the cross-validation results.

Sousa-Correia *et al.* (2007) have applied NIR spectroscopy for estimating the oil content of individual Holm oak (Quercus sp.) acorn kernels from different trees, sites and years. Three different technicians performed the extractions and the findings revealed the accuracy of the oil extraction procedure (standard deviation of 0.1%). Then, they developed NIR models with R^2 of 0.99 and root mean square error in cross validation of 0.37%. According to them, the varying moisture content within, and especially between, the years does not invalidate the results. The results of the analyses performed by the three people revealed good manageability of the procedure of oil extraction.

Hein *et al.* (2009) evaluated the robustness of the models based on NIR spectroscopy to predict wood basic density in Eucalyptus urophylla using two totally independent sample sets. In this study, the two data sets, wood density determinations and acquired NIR spectra, were carried out by two technicians (the other technician determined wood density and record NIR spectra of 105 wood samples while another evaluated 85 independent wood samples). One independent data set was used to build PLS-R models and applied the other to validate the results, and vice-versa. The predictive models developed from the radial surface NIR spectra provided the good adjustment with r^2p (determination coefficient in test set validation) varying from 0.79 to 0.85 and RPD (ratio of performance to deviation) ranging from 2.3 to 2.7 while the spectra measured on tangential and transversal wood surfaces supplied less robust regression models.

Despite many papers have demonstrated that NIR models present good performance in cross-validations or independent validations for wood density (Via *et al.*, 2003, 2005; Cogdill *et al.*, 2004; Mora *et al.*, 2008; Hein *et al.*, 2009), mechanical properties (Schimleck *et al.*, 2001; Kelley *et al.*, 2004; Fujimoto *et al.*, 2008) and chemical composition (Gierlinger *et al.*, 2002; Kelley *et al.*, 2004; Rodrigues *et al.*, 2006; Sousa-Correia *et al.*, 2007), there is still a lack for applications in real situations. While a number of studies have demonstrated that the NIR spectroscopy and multivariate analysis works well in laboratories where the conditions are controlled, limited studies have been done simulating in real industrial conditions, like pulp mills or wood processing factories. Thus, the ability of NIR spectroscopy for predicting wood traits on unknown samples from pre-established models is still not fully demonstrated and then, this issue requires further simulations.

Innovative NIR techniques in wood characterization

Hyperspectral imaging

Spectral imaging is a new technology combining spectral reflectance measurement and image processing technologies (Tatzer *et al.*, 2005). A hyperspectral imager relies on collecting and processing information from NIR spectra recorded from the biological material. According to Manley (2014) the main advantage of NIR hyperspectral imaging is that it facilitates visualisation of the distribution of different chemical components in a sample, as well physical (Mora *et al.*, 2011b), mechanical and anatomical (Duncker & Spiecker, 2009) variations along wood pieces.

The idea of hyperspectral imaging is to obtain a NIR spectrum for each pixel in the image with the purpose of identifying variations in wood properties and detecting defects or other characteristics. As the natural variations on the wood quality affect its use in industry, wood is highly suitable for NIR hyperspectral imaging. Several studies have been carried out in regard to this issue in wood and its products.

Tatzer *et al.* (2005) applied hyperspectral imaging for classifying paper and cardboards. They reported that the best classification performance was obtained using a combination of principal components analysis and linear discriminant analysis.

Duncker & Spiecker (2009) used NIR hyperspectral imaging for detecting and classifying compression wood in stem cross sections of Norway spruce. They successfully classified the cross-sectional areas by hyperspectral image analysis into severe compression wood, moderate compression wood, normal wood, and background /cracks.

Mora *et al.* (2011b) applied NIR hyperspectral imaging for the estimation of basic density and moisture content of loblolly pine wood discs. They reported promising calibration models for basic density (R^2 of 0.81) and MC (R^2 of 0.77) and suggested that hyperspectral imaging can be used for the estimation of basic density and MC of loblolly pine discs.

Thumm *et al.* (2010) applied NIR hyperspectral imaging for two-dimensional mapping the chemical composition on the transverse surface of Monterrey pine (*Pinus radiata*) wood discs. They developed NIR calibrations to visualise the distribution and variation of lignin, galactose and glucose in the discs with R^2/standard error of performance values of 0.84/1.48

for lignin; 0.87/0.68 for galactose; and 0.87/0.95 for glucose.

Meder & Meglen (2012) used NIR spectroscopy for predicting the severity of compression wood in Monterey pine samples using a subjective microscopic assessment of compression wood as the reference method. They reported a NIR-based calibration with R^2 of 0.84. Then, they achieved the spatial resolution of compression wood in board cross sections and discs from logs using an improvised NIR microscope based on a Zeiss trinocular microscope and, more recently, using a NIR hyperspectral line camera. According to them, compression wood was identifiable on the disc surfaces across the continuum from normal wood to severe compression wood.

Kobori *et al.* (2013) used visible-near-infrared hyperspectral imaging for monitoring the MC of wood samples during natural drying. They reported validations with high prediction accuracy indicating that hyperspectral imaging has a high potential for monitoring the water distribution of wood.

Smeland *et al.* (2016) studied the weather degradation effects on thin wood samples exposed outdoors from 0 days to 21 days and to ultraviolet (UV) radiation in a laboratory chamber using a hyperspectral camera in the NIR wavelength range (in transmission mode). They presented robust prediction models for weathering effects on wooden surfaces from spectra of earlywood and latewood extracted from the hyperspectral image cubes using different regression techniques.

Genetic studies on forest and wood combined with NIR technology

According to Posada *et al.* (2009), NIR spectroscopy applications seem promising in several fields linked to breeding study, notably for genetically improving quality. Because NIR spectroscopy can be considered as an incalculable source of information concerning wood and its properties (Hein & Chaix, 2014) this technology has been successfully applied in breeding programs for tree selection (Schimleck, 2008). According to Meder (2015) the ability to rapidly and non-destructively predict a number of wood quality traits using NIR spectra obtained from outer wood swarf collected by portable NIR at breast height in standing trees now provides tree breeders with information on traits of economic importance on all individual trees within a breeding trial - potentially thousands of trees.

Silva Perez *et al.* (2007) applied NIR spectroscopic models for estimating the content of lignin, cellulose, hemicelluloses, and extractives, as well as pulp yield, fibre length and wood density in 960 samples collected from a large number of maritime pine trees (belonging to 80 families obtained by crossing 18 mothers and 20 fathers). They used NIR calibrations with R^2 values higher than 0.9 to predict these data and carry out genetic studies. According to their findings, genetic calculations indicated that for a 1% rate of selection on mothers and fathers, genetically induced changes are possible with lignin content (−3.8%), cellulose content (+1.3%), pulp yield (+1.8%), fibre length in pulps (+0.17 mm) and wood density (+50 kg/m^3).

Lepoittevin *et al.* (2011) also developed NIR calibrations for assessing chemical properties of wood in maritime pine and estimated genetic parameters of wood chemistry traits across a large genetic background in a progeny trial and clonally replicated progenies. Based on these predictions, they reported heritability estimates from 0.21 to 0.25 for lignin; from 0.17 to 0.18 for cellulose; and 0.17 to 0.55 to hemicelluloses. They pointed out that wood chemistry traits were genetically inter-correlated (*e.g.,* negatively between lignin and cellulose), whereas correlations with growth were not significant, indicating that growth and chemical properties could be improved independently.

Brawner *et al.* (2012) evaluated a series of spotted gum (*Corymbia citriodora*) progeny trials in Queensland, Australia for generating genetic parameter estimates and to predict genetic gain for pulp production. They pointed out that the NIR based predictions of average wood density and pulp yield indicate the species has considerable potential as a pulpwood crop.

Mandrou *et al.* (2012) applied NIR-models for estimating lignin content and syringyl to guaiacyl ratio (S/G) in Eucalypt wood (in 33 *Eucalyptus urophylla* full-sib families). They reported a high value of narrow sense heritability for lignin content (h^2=0.85) and S/G ratio (h^2=0.62) indicating that these traits are under strong genetic control.

Hein *et al.* (2012) used NIR spectroscopy calibrations for evaluating the genetic and environmental control of microfibril angle (MFA), wood density, Klason lignin content and S/G ratio in 340 control-pollinated progenies of *Eucalyptus urophylla* with 14 years. They found moderate to high heritability estimates (h^2) for MFA (h^2=0.43), density (h^2=0.61), S/G ratio (h^2=0.71) and Klason lignin (h^2=0.76). These findings allow discussion of their impact on breeding strategies for pulpwood, fuelwood and sawn timber production.

Hung *et al.* (2015) evaluated genetic parameters of basic density, Kraft pulp yield, modulus of elasticity and microfibril angle in *E. pellita* wood grown in Vietnam using NIR spectroscopy. They stated that multi-trait selection for growth and wood properties can lead to more productive populations of *E. pellita* with improved productivity and wood and pulp properties.

Estopa *et al.* (2017) applied NIR-based models for estimating chemical properties of *Eucalyptus benthamii* wood at 4 years old. They stated that the lignin and extractive estimates can be applied in breeding programmes of *E. benthamii* for early selections. In regard to the genetic studies using NIR spectra taken on foliage, Abasolo *et al.* (2013) examined the potential of NIR spectroscopy for field diagnosis of hybrids between *Corymbia* species from NIR spectra recorded on foliage of 383 hybrid and 533 parental seedlings grown in a common garden. Using PLS-DA, the mean assignment rates for the three hybrid groups ranged from 76 to 90% while the F1 taxon assignment rates were usually higher than those for parents at 100% and 72%, respectively. Meder *et al.* (2014) also recorded NIR spectra from foliage, but in *Pinus* species, and classified the extent of hybridisation for the F1 and backcross progeny of their hybrids. The findings indicate that this technique has the potential to confirm and assess the extent of hybridisation in *Pinus* species. It might be possible to use NIR spectra from foliage to recover taxon information of seedlings, for instance, in extreme situations where trial records are lost or trial plot labelling is missing (Meder *et al.*, 2014).

Few studies have investigated the genetic and environmental control from the NIR signature variations of vegetal materials. The advantage of the estimation of heritability of wood or trees from NIR spectra is that this approach does not require traditional wet chemistry analysis of wood by standard methods for selecting potential trees (and their wood), which are expensive and time consuming.

In perennial crops, Posada *et al.* (2009) used NIR spectral signatures to characterize coffee varieties and indicated how this typical signature can be used in breeding to assist in selection. Their findings suggest that IR spectroscopy can be used by breeders for indirect selection on the basis of biochemical composition, and consequently on cup quality, in the coffee tree, but probably also in other species.

Greaves *et al.* (1996) evaluated the genetic control of NIR spectra recorded from the wood powder of 7-year-old *Eucalyptus* trees from 94 open-pollinated families founding that the NIR bands presenting high genetic control showed low family by site interaction. Hein & Chaix (2014) investigated the extent of NIR spectral variations recorded on solid eucalyptus wood from clonal tests under genetic and environmental control. They showed that variations in some regions within NIR spectra are controlled by genetic effects presenting heritability estimates greater than 50%. As the findings appear to be repeatable along the stem, this confirms that wood breeders should focus at diameter breast height for sampling increment cores and performing the NIR analysis.

Final considerations

The development of rapid, accurate and industrially feasible methods have become necessary for characterization and classification of raw material in the forestry-related industry, especially for pulp and paper or sawn wood, since these companies require methods able to monitor the quality of a large number of samples.

The main challenges to be overcome in order to make the NIR spectroscopy an applicable, reliable technique in field conditions are moisture and portability. Fresh wood, bark, fruits, seeds and leaves can present high levels of moisture and NIR spectra is very sensitive from 1400 to 1900 nm, where two main hydroxyl absorption peaks occurs. Moreover, there is a need for portable NIR equipment capable to record NIR spectra with low noise and low sensitivity to temperature and humidity variations of the air, as well as other common sources of variation to forest environments. Studies concerning the sample preparation effects on NIR calibrations and investigations about the robustness of the calibrations also are required.

Many researches have demonstrated that NIR spectroscopy and multivariate analysis work well in laboratories where the conditions are controlled. However, there is still a gap between laboratory research and real situations concerning the performance of NIR models in wood. Studies showing the success of NIR-based models in real situations, taking into account variations in moisture, granulometry, surface quality, temperature, and other sources of variation present in factories conditions would be useful.

References

Abasolo M, Lee DJ, Raymond C, Meder R, Shepherd M, 2013. Deviant near-infrared spectra allows identification of *Corymbia* hybrids. Forest Ecol Manag 304: 121-131. https://doi.org/10.1016/j.foreco.2013.04.040

Adedipe OE, Dawson-Andoh B, 2008. Predicting moisture content of yellow-poplar (*Liriodendron tulipifera*) veneer using near infrared spectroscopy. For Prod J 58: 28-33.

Birkett MD, Gambino MJT, 1989. Estimation of pulp kappa number with near infrared spectroscopy. Tappi J 72: 193-197.

Bokobza L, 1998. Near infrared spectroscopy. J Near Infrared Spectrosc 6: 3-17. https://doi.org/10.1255/jnirs.116

Brawner JT, Meder R, Lee DJ, Dieters M, 2012. Selection of *Corymbia citriodora* for pulp productivity. South Forests 74: 121-131. https://doi.org/10.2989/20702620.2012.701418

Brereton RG, 2003. Chemometrics: data analysis for the laboratory and chemical plant. John Wiley & Sons Ltd, Chichester, England. 489 pp. https://doi.org/10.1002/0470863242

Cogdill RP, Schimleck LR, Jones PD, Peter GF, Daniels RF, Clark A, 2004. Estimation of the physical wood properties of *Pinus taeda* L radial strips using least square support vector machines. J Near Infrared Spectrosc 12: 263-269. https://doi.org/10.1255/jnirs.434

Cooper PA, Jeremic D, Radivojevic S, Ung YT, Leblon B, 2011. Potential of near-infrared spectroscopy to characterize wood products. Can J For Res 41: 2150-2157. https://doi.org/10.1139/x11-088

Defo M, Taylor M, Bond B, 2007. Determination of moisture content and density of fresh-sawn red oak lumber by near-infrared spectroscopy. For Prod J 57: 68-72.

Downes GM, Meder R, Ebdon N, Bond H, Evans R, Joyce K, Southerton S, 2010. Radial variation in cellulose content and Kraft pulp yield in *Eucalyptus nitens* using near-infrared spectral analysis of air-dry wood surfaces. J Near Infrared Spectrosc 18: 147-155. https://doi.org/10.1255/jnirs.875

Duncker P, Spiecker H, 2009. Detection and classification of Norway spruce compression wood in reflected light by means of hyperspectral image analysis. IAWA J 30: 59-70. https://doi.org/10.1163/22941932-90000203

Easty DB, Berben SA, DeThomas FA, Brimmer PJ, 1990. Near-infrared spectroscopy for the analysis of wood pulp: quantifying hardwood-softwood mixtures and estimating lignin content. Tappi J 73: 257-261.

Estopa RA, Milagres FR, Oliveira RA, Hein PRG, 2017. NIR spectroscopic models for phenotyping wood traits in breeding programs of Eucalyptus benthamii. Cerne 22: 367-375. https://doi.org/10.1590/01047760201723032319

Fujimoto T, Kurata Y, Matsumoto K, Tsuchikawa S, 2008. Application of near infrared spectroscopy for estimating wood mechanical properties of small clear and full length lumber specimens. J Near Infrared Spectrosc 16: 529-537. https://doi.org/10.1255/jnirs.818

Gierlinger N, Schwanninger M, Hinterstoisser B, Wimmer R, 2002. Rapid determination of heartwood extractives in *Larix* sp by means of Fourier transform near infrared spectroscopy. J Near Infrared Spectrosc 10: 203-214. https://doi.org/10.1255/jnirs.336

Glass SV, Zelinka SL, 2010. Moisture relations and physical properties of wood. In: Wood handbook - Wood as an engineering material, Chapter 4. Centennial ed, general technical report FPL-GTR-190. Pp: 1-19 USDA Forest Service Forest Products Laboratory, Madison.

Greaves BL, Schimleck LR, Borralho NMG, Michell AJ, 1996. Genetic control and repeatability of near infrared reflectance from *Eucalyptus nitens* woodmeal. Appita J 49: 423-426.

Haddadi A, Hans G, Leblon B, Pirouz Z, Tsuchikawa S, Naderd J, Groves K, 2016. Determination of optical parameters and moisture content of wood with visible-near infrared spectroscopy. J Near Infrared Spectrosc 24: 571-585. https://doi.org/10.1255/jnirs.1174

Hans G, Leblon B, Stirling R, Nader J, LaRocque A, Cooper P, 2012. Monitoring of moisture content and basic specific gravity in black spruce logs using a handheld MEMS-based near-infrared spectrometer. The Forestry Chronicle 89: 605-618.

Hein PRG, Chaix G, 2014. NIR spectral heritability: a promising tool for wood breeders? J Near Infrared Spectrosc 22: 141-147. https://doi.org/10.1255/jnirs.1108

Hein PRG, Lima JT, Chaix G, 2009. Robustness of models based on near infrared spectra to predict the basic density in *Eucalyptus urophylla* wood. J Near Infrared Spectrosc 17: 141-150. https://doi.org/10.1255/jnirs.833

Hein PRG, Bouvet JM, Mandrou E, Vigneron P, Clair B, Chaix G, 2012. Age trends of microfibril angle inheritance and their genetic and environmental correlations with growth density and chemical properties in *Eucalyptus urophylla* ST Blake wood. Ann For Sci 69: 681-691. https://doi.org/10.1007/s13595-012-0186-3

Hoffmeyer P, Pedersen JG, 1995. Evaluation of density and strength of Norway spruce wood by near-infrared reflectance spectroscopy. Holz als Roh- und Werkstoff 53: 165-170. https://doi.org/10.1007/BF02716418

Hung TD, Brawner JT, Meder R, Lee DJ, Southerton SG, Thinhand HH, Dieters MJ, 2015. Estimates of genetic parameters for growth and wood properties of *Eucalyptus pellita* F Muell to support tree breeding in Vietnam. Ann Forest Sci 72: 205-217. https://doi.org/10.1007/s13595-014-0426-9

Kelley SS, Rials TG, Snell R, Groom LH, Sluiter A, 2004. Use of near infrared spectroscopy to measure the chemical and mechanical properties of solid wood. Wood Sci Technol 38: 257-276. https://doi.org/10.1007/s00226-003-0213-5

Kobori H, Gorretta N, Rabatel G, Bellon-Maurel V, Chaix G, Roger JM, Tsuchikawa S, 2013. Applicability of Vis-NIR hyperspectral imaging for monitoring wood moisture content (MC). Holzforschung 67: 307-314. https://doi.org/10.1515/hf-2012-0054

Leblon B, Adedipe O, Hans G, Haddadi A, Tsuchikawa A, Burger J, Stirling R, Pirouz Z, Groves K, Nader J, LaRocque A, 2013. A review of near-infrared spectroscopy for monitoring moisture content and density of solid wood. The Forestry Chronicle 89: 595-606. https://doi.org/10.5558/tfc2013-111

Lepoittevin C, Rousseau JP, Guillemin A, Gauvrit C, Besson F, Hubert F, da Silva Perez D, Harvengt L, Plomion C, 2011. Genetic parameters of growth straightness and wood chemistry traits in *Pinus pinaster*. Ann For Sci 68: 873-884. https://doi.org/10.1007/s13595-011-0084-0

Mandrou E, Hein PRG, Villar E, Vigneron P, Plomion C, Gion JM, 2012. A candidate gene for lignin composition in *Eucalyptus*: *cinnamoyl-CoA* reductase (CCR). Tree Genet Genom 8: 353-364. https://doi.org/10.1007/s11295-011-0446-7

Manley M, 2014. Near-infrared spectroscopy and hyperspectral imaging: non-destructive analysis of biological materials. Chem Soc Rev 43: 8200-8214. https://doi.org/10.1039/C4CS00062E

Mark H, Workman J, 2007. Chemometrics in spectroscopy. Academic Press, London, UK. 526 pp.

Meder R, 2015. The magnitude of tree breeding and the role of near infrared spectroscopy. NIR News 26: 8-10. https://doi.org/10.1255/nirn.1521

Meder R, Brawner JT, Downes GM, 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. J Near Infrared Spectrosc 19: 421-429. https://doi.org/10.1255/jnirs.954

Meder R, Meglen R, 2012. Near infrared spectroscopic and hyperspectral imaging of compression wood in *Pinus radiata* D Don. J Near Infrared Spectrosc 20: 583-589. https://doi.org/10.1255/jnirs.1001

Meder R, Kain D, Ebdon N, Macdonell P, Brawner JT, 2014. Identifying hybridisation in *Pinus* species using NIR spectroscopy of foliage. J Near Infrared Spectrosc 22: 337-345. https://doi.org/10.1255/jnirs.1127

Mora CR, Schimleck LR, Isik F, 2008. Near infrared calibration models for the estimation of wood density in *Pinus taeda* using repeated sample measurement. J Near Infrared Spectrosc 16: 517-528. https://doi.org/10.1255/jnirs.816

Mora CR, Schimleck LR, Clark A, Daniels RF, 2011a. Determination of basic density and moisture content of merchantable loblolly pine logs by near-infrared spectroscopy. J Near Infrared Spectrosc 19: 391-399. https://doi.org/10.1255/jnirs.947

Mora CR, Schimleck LR, Yoon S-C, Thai CN, 2011b. Determination of basic density and moisture content of loblolly pine wood disks using a near-infrared hyperspectral imaging system. J Near Infrared Spectrosc 19: 401-409. https://doi.org/10.1255/jnirs.948

Næs T, Isaksson T, Fearn T, Davies T, 2002. A user-friendly guide to multivariate calibration and classification. NIR Publications, Chichester, UK. 344 pp.

Pasquini C, 2003. Near infrared spectroscopy: fundamentals, practical aspects and analytical applications. J Braz Chem Soc 14: 198-219. https://doi.org/10.1590/S0103-50532003000200006

Pereira H, Santos AJA, Anjos O, 2016. Fibre morphological characteristics of Kraft pulps of *Acacia melanoxylon* estimated by NIR-PLS-R models. Materials 9 (1): 8. https://doi.org/10.3390/ma9010008

Posada H, Ferrand M, Davrieux F, Lashermes P, Bertrand B, 2009. Stability across environments of the coffee variety near infrared spectral signature. Heredity 102: 113-119. https://doi.org/10.1038/hdy.2008.88

Raymond CA, 2002. Genetics of *Eucalyptus* wood properties. Ann For Sci 59: 525-531. https://doi.org/10.1051/forest:2002037

Rodrigues J, Alves A, Pereira H, da Silva Perez D, Chantre G, Schwanninger M, 2006. NIR PLSR results obtained by calibration with noisy low-precision reference values: Are the results acceptable? Holzforschung 60: 402-408. https://doi.org/10.1515/HF.2006.063

Sandak A, Sandak J, Böhm K, Zitek A, Hinterstoisser B, 2016. Near infrared spectroscopy as a tool for in-field determination of log/biomass quality index in mountain forests. J Near Infrared Spectrosc 24: 587-594. https://doi.org/10.1255/jnirs.1231

Sandak J, Sandak A, Meder R, 2016. Tutorial - Assessing trees wood and derived products with near infrared spectroscopy: hints and tips. J Near Infrared Spectrosc 24: 485-505. https://doi.org/10.1255/jnirs.1255

Santos AJA, Alves AMM, Simões RMS, Pereira H, Rodrigues J, Schwanninger M, 2012. Estimation of wood basic density of *Acacia melanoxylon* (R Br) by near infrared spectroscopy. J Near Infrared Spectrosc 20: 267-274. https://doi.org/10.1255/jnirs.986

Santos AJA, Anjos O, Pereira H, 2015. Estimation of *Acacia melanoxylon* unbleached Kraft pulp brightness by NIR spectroscopy. Forest Syst 24 (2): eRC03. https://doi.org/10.5424/fs/2015242-07580

Schimleck LR, 2008. Near-infrared spectroscopy: A rapid non-destructive method for measuring wood properties and its application to tree breeding. N Z J For Sci 38: 14-35.

Schimleck LR, Raymond CA, Beadle CL, Downes GM, Kube PD, French J, 2000. Applications of NIR spectroscopy to forest research. Appita J 53: 458-464.

Schimleck LR, Evans R, Ilic J, 2001. Estimation of *Eucalyptus delegatensis* wood properties by near infrared spectroscopy. Can J For Res 31: 1671-1675. https://doi.org/10.1139/x01-101

Schwanninger M, Rodrigues JC, Fackler K, 2011. A review of band assignments in near infrared spectra of wood and wood components. J Near Infrared Spectrosc 19: 287-308. https://doi.org/10.1255/jnirs.955

Silva Perez D, Guillemain A, Alazard P, Plomion C, Rozenberg P, Rodrigues JC, Alves A, Chantre G, 2007. Improvement of *Pinus pinaster* Ait elite trees selection by combining near infrared spectroscopy and genetic tools. Holzforschung 61: 611-622. https://doi.org/10.1515/HF.2007.118

Smeland KA, Liland KH, Sandak J, Sandak A, Gobakken LR, Thiis TK, Burud I, 2016. Near infrared hyperspectral imaging in transmission mode: assessing the weathering of thin wood samples. J Near Infrared Spectrosc 24: 595-604. https://doi.org/10.1255/jnirs.1253

So CL, Via B, Groom LH, Schimleck LR, Shupe TF, Kelley SS, Rials TG, 2004. Near-infrared spectroscopy in the forest products industry. For Prod J 54 (3): 6-16.

Sousa-Correia C, Alves A, Rodrigues JC, Ferreira-Dias S, Abreu JM, Maxted N, Ford-Lloyd B, Schwanninger M, 2007. Oil content estimation of individuals kernels of *Quercus ilex* subsp *rotundifolia* [(Lam) O Schwarz] acorns by Fourier transform near infrared spectroscopy and partial least squares regression. J Near Infrared Spectrosc 15: 247-260. https://doi.org/10.1255/jnirs.733

Tatzer P, Wolf M, Panner T, 2005. Industrial application for inline material sorting using hyperspectral imaging in the NIR range Real-Time. Imaging 11: 99-107.

Thumm A, Riddell M, Nanayakkara B, Harrington J, Meder R, 2010. Near infrared hyperspectral imaging applied to mapping chemical composition in wood samples. J Near Infrared Spectrosc 18: 507-515. https://doi.org/10.1255/jnirs.909

Thygesen L, 1994. Determination of dry matter content and basic density of Norway spruce by near-infrared reflectance and transmittance spectroscopy. J Near Infrared Spectrosc 2: 127-135. https://doi.org/10.1255/jnirs.39

Thygesen LG, Lundqvist SO, 2000. NIR measurement of moisture content in wood under unstable temperature conditions Part 2 Handling temperature fluctuations. J Near Infrared Spectrosc 8: 191-199. https://doi.org/10.1255/jnirs.278

Tsuchikawa S, 2007. A review of recent near infrared research for wood and paper. Appl Spectrosc Rev 42: 43-71. https://doi.org/10.1080/05704920601036707

Tsuchikawa S, Schwanninger M, 2013. A review of recent near-infrared research for wood and paper (Part 2). Appl Spectrosc Rev 48: 560-587. https://doi.org/10.1080/05704928.2011.621079

Tsuchikawa S, Kobori H, 2015. A review of recent application of near infrared spectroscopy to wood science and technology. J Wood Sci 61: 213-220. https://doi.org/10.1007/s10086-015-1467-x

Tsuchikawa S, Hayashi K, Tsutsumi S, 1992. Application of near infrared spectrophotometry to wood 1 Effects of the surface-structure. Mokuzai Gakkaishi 38: 128-136.

Verryn SD, 2008. Breeding for wood quality - A perspective for the future. N Z J For Sci 38: 5-13.

Via BK, Shupe TF, Groom LH, Stine M, So CL, 2003. Multivariate modelling of density strength and stiffness from near infrared spectra for mature juvenile and pith wood of longleaf pine (*Pinus palustris*). J Near Infrared Spectrosc 11: 365-378. https://doi.org/10.1255/jnirs.388

Via BK, So CL, Shupe TF, Stine M, Groom LH, 2005. Ability of near infrared spectroscopy to monitor air-dry density distribution and variation of wood. Wood Fiber Sci 37: 394-402.

Wallbäcks L, Edlund U, Norden B, Berglund I, 1991. Multivariate characterization of pulp using 13C NMR FTIR and NIR. Tappi J 74: 201-206.

Watanabe K, Hart JF, Mansfield SD, Avramidis S, 2010. Near infrared technology applications for quality control in wood processing. Proc COST E53 Conf, Edinburgh (UK), pp: 332-341.

Watanabe K, Mansfield SD, Avramidis S, 2011. Application of near-infrared spectroscopy for moisture-based sorting of green hem-fir timber. J Wood Sci 57: 288-294. https://doi.org/10.1007/s10086-011-1181-2

Wright JA, Birkett MD, Gambino MJT, 1990. Prediction of pulp yield and cellulose content from wood samples using near infrared reflectance spectroscopy. Tappi J 73: 164-166.