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SHORT COMMUNICATION

Real-Time Determination of Wood Moisture Content Using Dielectric Properties: A Case Study on *Falcataria falcata*

H. I. S. Hansani*, S. S. Abeywickrama, N. T. Wickramasuriya

Highlights

- A capacitance-based dielectric measurement method is proposed for real-time wood moisture estimation
- The approach provides a faster and more efficient alternative to traditional oven-drying techniques
- The method is suitable for industrial applications requiring rapid and non-destructive moisture assessment

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Real-Time Determination of Wood Moisture Content Using Dielectric Properties: A Case Study on *Falcataria falcata*

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Abstract: The direct determination of the moisture content of wood is based on the oven drying technique, which is a time-consuming and expensive approach. In this study, capacitance was used as the core factor to determine the moisture content of *Falcataria falcata* (‘*mara’* in Sinhala) using a parallel plate capacitor. Wood samples were allowed to absorb water forcefully, surface water was removed, and their weights were measured at different time intervals while they were kept in a microwave oven at 373 K. Corresponding moisture content was calculated by mass differences due to evaporation. The capacitances of wood samples were measured for different moisture levels at room temperature using an Inductance (L), Capacitance (C), and Resistance (R) meter, which applied a constant and optimum frequency of 10 kHz. The cubic regression model was chosen as the best fit model, since it showed 98.46% and 98.43% for adjusted R^2 and R^2 values, respectively. The average error of the regression model was found as 1.6915×10^{-14}. The proposed parallel plate capacitor method demonstrated 97.7% accuracy with respect to the standard method. This indicates that the proposed method is highly reliable and can serve as an effective alternative to the standard technique for measuring the moisture content of wood.

***Keywords*:** Dielectric; Fiber Saturation Point; Moisture Content; Microwave; Wood

INTRODUCTION

Water makes up a large portion of trees and has a complex structure. The fundamental fact is that wood is hygroscopic, meaning wood can absorb water or moisture based on the environmental conditions and acts as a sponge. Water is stored in two forms: free water and bound water. Before the timber from a tree is turned into consumer goods, most of this water needs to evaporate to avoid shrinkage, cracks, and other physical changes. When the moisture level decreases below the fiber saturation point (FSP), wood starts to change its shape, causing the above-mentioned changes. This critical moisture value stands at around 30% in wood samples in temperate regions. The wood drying process is very common before converting wood into a consumer product. Drying wood by any means is expensive, so operators are constantly on the alert to reduce costs **(**Majka & Sydor, 2023)

Wood is classified as hardwood or softwood depending on its physical structure. Since the a permeability difference between softwood and hardwood, absorbability changes. During the drying process, elimination of free water occurs up to the needed level. The drying process for wood is not uniform and proceeds at a slower rate until the wood reaches an equilibrium moisture content (MC). The drying process is affected by both wood and environmental elements, such as the diameter, density, and relative humidity of the logs, as well as temperature, wind speed, and wind direction (Zanuncio et al., 2015; Han et al., 2019).

Craftsmen and scientists have the most responsible roles during the processes of manufacturing productive products, and investigations and analysis using wood. They have the skill to determine whether the moisture content is appropriate for production or not. In the case of direct determination of moisture content of wood, it is time-consuming and expensive work. The Kiln dry method, the Distillation method, and the Extraction method are some popular direct methods used in measuring moisture content. Even today, the world uses the oven-drying method or the conventional method as a common standard method or the reference method because of the relatively high accuracy. In industrial applications, the moisture content of wood needs to be detected quickly. As alternatives to these, indirect methods like capacitance method, electrical resistance method, NIR, microwave method, radiometric method, X-ray, and CT methods were found. However, real-time determination of moisture content is still a challenge. Among these methods, the capacitance method is the most commonly available method, which came to industry and for general usage, since the transmission of an electric field is much more convenient in a dielectric medium and is a cost-effective method (Morón et al., 2016).

The dielectric characteristic of wood is crucial for professionals in forestry, materials science, electrical engineering, and other professions based on wood. Cellulose, hemicellulose, and lignin make up most of its composition, and wood is a naturally occurring composite material with a complex heterogeneous structure, but this can be studied based on the electrical properties.

Dielectric qualities include a material’s conductivity and permittivity, which describe how the material reacts to an electric field. These characteristics of wood are affected by species, density, anatomical structure, and moisture content. Among other things, examining the dielectric characteristics of wood provides important information about its moisture

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content, structural soundness, and appropriateness for uses. For example, changes in the dielectric constant might signal changes in moisture content, which is important to determine the quality of the wood and variations under different environmental conditions (Korkua & Sakphrom, 2020).

Dielectric spectroscopy, impedance analysis, microwave measurements, and capacitance methods are just a few methods used by researchers to analyze the dielectric characteristics of wood in a variety of frequency ranges and environmental settings. These analyses support the development of wood-based materials for a range of applications, the optimization of wood processing methods, and the improvement of product quality. Using the parallel plate capacitance method, one can investigate the dielectric characteristics of various materials, including wood, effortlessly and efficiently. Using this technique, a capacitor is created by sandwiching the material of interest between two conducting plates. Through varying the temperature or frequency of this system, researchers can measure the capacitance and obtain important dielectric properties of the material (Bhuiyan et al., 2007). This method provides useful information on the electrical properties of wood, such as its moisture content, variations in density, and structural features. Moreover, this can be applied to examine the impact of environmental variables like temperature and humidity on the dielectric characteristics of wood. Researchers can examine the ways in which these elements affect the electrical behavior of wood for the real-time determination of wood moisture, as it is crucial and important in the wood industry. Important information about how dielectric characteristics respond to environmental factors can be obtained by performing experiments that target humidity levels and temperature variations in different regions (Glass & Zelinka, 2010).

Because of its ease of use and adaptability, the parallel plate capacitance method is especially well-suited for researching the dielectric characteristics of wood. Controlled experimentation is possible since wood samples are relatively simple to prepare and insert between the plates. Furthermore, measurements over a broad frequency range from high frequencies typical of microwave applications to low frequencies pertinent to DC circuits are possible with this technology. (Lev et al., 2021)

Using the proper equipment, such as an impedance analyzer or capacitance meter, LCR meters, the system's capacitance can be measured throughout the experiment. Researchers can determine important dielectric characteristics of the wood sample, such as its relative permittivity (dielectric constant), loss tangent, and conductivity, by examining how the capacitance varies with various parameters (Morón et al., 2016). The main objective of this study is to develop and validate a reliable parallel plate capacitor method for measuring the moisture content of wood, providing a faster and non-destructive alternative to standard techniques. In this work, wood samples from *Falcataria Falcata* were used due to their common use in construction and furniture, making accurate moisture determination practically important.

MATERIALS AND METHODS

The method of the capacitive technique is based on measuring the electric field formed between the capacitor plates. The material placed between these plates acts as a dielectric, influencing the capacitance value. As the dielectric constant changes due to moisture variations, the capacitance and impedance of the device also change accordingly. The capacitance (C) of a parallel plate capacitor depends on the dielectric permittivity (ε), plate area (A), and plate separation (d). When A and d remain constant, the capacitance varies with the material's permittivity, which in turn is influenced by its moisture content (Korkua & Sakphrom, 2020). Here, $\varepsilon = \varepsilon_0\varepsilon_r$

$$C = \frac{\varepsilon A}{d} \quad (1)$$

Generally, ε_r is a complex quantity. The dielectric constant depends on the insulation characteristics of the dielectric medium within an electric field. It indicates how permeable the material is for electrical fields and depends on the specimen and vacuum as the dielectric and medium, respectively (Bhuiyan et al., 2007).

Wood's moisture content (MC) is estimated using the method described, which is based on variations in the material's dielectric permittivity at two distinct frequencies. Estimating the moisture content can be done by measuring the amount that the dielectric properties of the material change, which is determined by the two frequencies (Lev et al., 2021).

$$\varepsilon_{r1} - \varepsilon_{r1} = \frac{(C1-C2)}{d(\varepsilon_0 A)} \quad (2)$$

Where, ε_{r1} and ε_{r2} are the relative dielectric constants at two different frequencies, (C1 - C2) are the capacitances at these frequencies. This equation helps in determining the change in the dielectric properties, which is related to moisture content. From (Morón et al., 2016), (C1 - C2) was determined to be a good estimator and indicator of the MC values. The MC values were obtained by combining the two frequencies' two parameters, the dissipation factor D and phase angle θ, into an empirical equation with (C1-C2), thus resulting in the MC values (Kandala & Nelson, 1990; Kandala & Nelson, 2007)

$$MC = A_0 + A_1(C_1 - C_2) + A_1(C_1 - C_2)^2 + A_3\left[\frac{(\theta_1-\theta_2)}{(C_1 - C_2) + 2(D_1 - D_2)} - (C_1 - C_2)(D_1 - D_2)\right] \quad (3)$$

When estimating moisture content, the dissipation factor (D) and phase angle (θ) are crucial, but they can be made simpler by taking into account just one frequency. For one frequency phase angle θ can be ignored. Since the moisture content is higher and the dielectric constant fluctuates less at low frequencies, D is small. Therefore, D should also be ignored. Finally, the equation can be written as,

$$MC = A_0 + A_1C + A_2C^2 \quad (4)$$

A parallel plate capacitor system was constructed using two Aluminum electrodes. The distance between the metal plates of the system could be adjusted according to the thickness of the wood sample, and the plates were attached to a rigid support that allows one to keep the sheets in a parallel manner under all circumstances. LCR-916(100

kHz) was used to measure the capacitance of the wood sample by applying a 10 kHz constant frequency.

Uniform, defect-free, and identical samples of *Moluccan albizia* wood were selected, and the dimensions of the samples were obtained as 20 cm × 20 cm × 20 cm. These samples were subjected to forceful absorption of water by dipping them in the water for more than 5 days until saturation was reached. Surface water on the samples was wiped out, and separately measured the mass of each sample and they were kept inside the microwave oven at 373 K for different time intervals, subjected to evaporation of water in order to calculate the initial moisture content at each situation. Then the capacitance of each sample was measured using the parallel plate capacitor system. This procedure was repeated until two consecutive mass measurements were the same in each wood sample. The moisture contents of the wood samples in each situation at room temperature (302K) were calculated according to the following equation. (Teodorescu et al., 2021). To prevent further absorption of moisture from the external environment during the cooling process, the wood sample was placed in a sealed bag while it was brought to room temperature.

$$MC(\%) = \frac{\text{Initial mass of the sample before drying-Mass of the dried sample}}{\text{Initial mass of the sample}} \times 100\% \quad (5)$$

A regression equation was determined by using Minitab Software. The Regression analysis and ANOVA test were used to validate the model. Randomly selected wood samples were tested for their moisture contents using the proposed method, and the results were compared with the % moisture content calculated using the reference method.

RESULTS AND DISCUSSION

Moisture content was calculated using Equation (5) for many events during the drying process of wood samples and it was recorded in relation to the corresponding capacitance values, as illustrated in Figure 1. Based on the experimental data, a regression model was developed using Minitab software. Regression analysis and an ANOVA test were conducted to identify the most suitable model. Among the models tested, including linear and polynomial regressions, the cubic regression model was selected as the best fit, as it yielded the highest R^2 and adjusted R^2 values as 98.46% and 98.43% respectively as shown in Figure 2.

The regression equation for the model:

$$\text{Moisture Content} = -5.663 + 0.1368 \times \text{Capacitance} - 0.000144 \times \text{Capacitance}^2$$

The predicted and the experimental moisture contents of wood were studied using the software. Figure 3 shows the variation between the predicted and experimental moisture content of wood at room temperature.

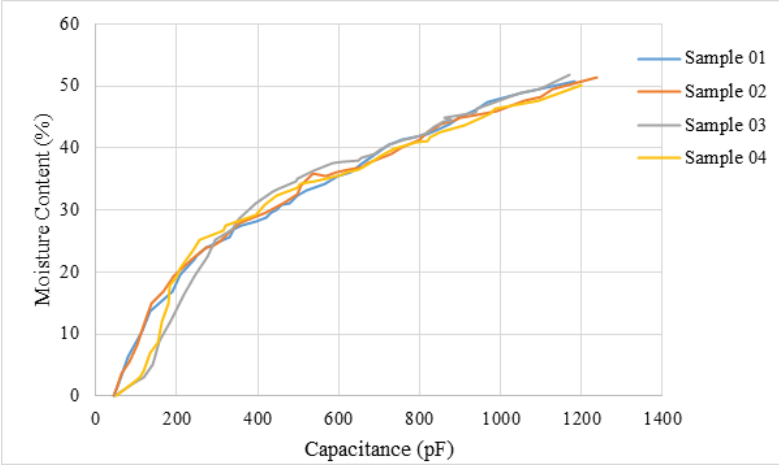


Figure 1: The relationship between the moisture content (%) of four wood samples and its capacitance at room temperature.

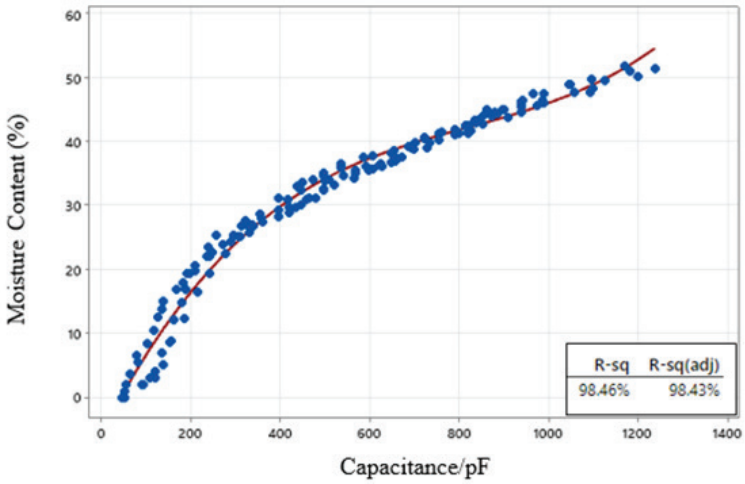


Figure 2: Fitted line plot for moisture content (%) of wood versus cubic value of the capacitance (pF).

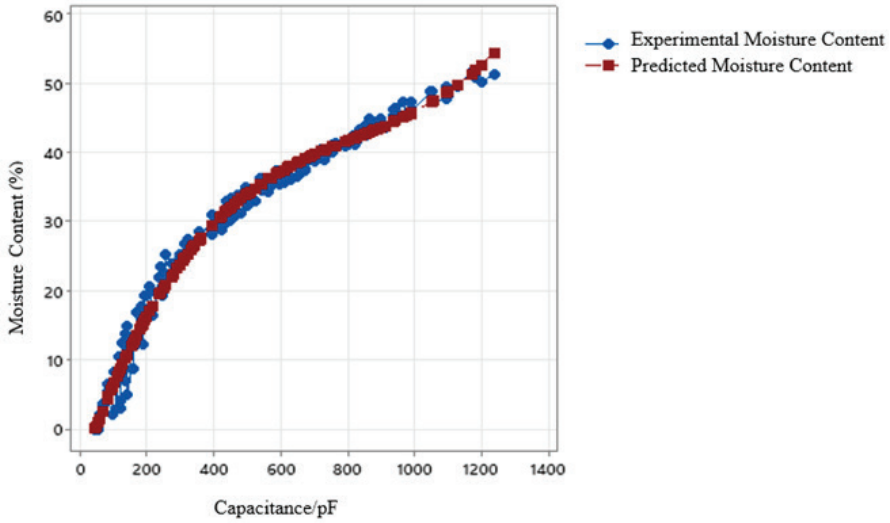


Figure 3: The variation of the predicted and the experimental moisture contents of wood at room temperature

The average error of the regression model is 1.6915×10^{-14}. The normal probability of the residual distribution is positioned closer to the normal line, and the histogram for the residual distribution is symmetric around 0.0. The moisture contents of a few randomly selected wood samples were estimated using the model and compared with the standard method, which gives 97.7% accuracy relative to the reference method.

CONCLUSION

This study confirms that the dielectric properties or capacitance of wood can serve as a reliable parameter for predicting the moisture content of wood samples, in comparison to the standard oven-drying method. Owing to its simplicity and low cost, this nondestructive method can be effectively implemented in economically constrained settings. The proposed dielectric approach, based on a parallel plate capacitor structure with a 1 cm plate separation and operated at a constant frequency of 10 kHz, demonstrated an accuracy of 97.7% relative to the oven-drying technique. The results indicate that dielectric properties measured at low frequencies can successfully predict wood moisture content. This method allows the measurement of moisture content up to 50%, considering relevant environmental factors. It offers a practical advantage for industrial applications, enabling real-time moisture assessment within minutes, in contrast to the lengthy and costly oven-drying process. However, since this study was conducted on a specific wood species under controlled environmental conditions, the findings may not be directly generalizable to all wood types or environmental scenarios. Variations in dielectric properties can arise due to differences in grain structure, moisture distribution, and sample geometry, as well as environmental factors such as temperature and relative humidity. Therefore, further validation is recommended using a broader range of wood species, varying sample thicknesses, and different environmental conditions.

DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest

FUNDING INFORMATION

The authors declare that no funds, grants, or other support were received for the conduct of this study

DATA AVAILABILIY STATEMENT

The data that support the findings of this study were generated through experiments conducted by the authors. These data are available from the corresponding author upon reasonable request.

AUTHOR CONTRIBUTION

Research and manuscript writing: **H.I.S.H.;** Supervision, guidance, and manuscript reviewing: **N.T.W., S.S.A.**

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