Use of a chlorophyll meter as a decision-support tool for nitrogen management in coffee fields

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Abstract.
Coffee is a crop with high nitrogen (N) demand in Brazil; therefore, improving N use efficiency in coffee plantations can have significant environmental and economic impacts. Decisions regarding N application rates in coffee cultivation are often empirical or based on multiple factors, including expected yield and plant N status as determined by leaf N concentration. Traditionally, leaf N concentration is obtained through laboratory chemical analysis, a process that may take several days and limits its applicability for timely decision-making. Alternatively, chlorophyll meters offer an inexpensive, rapid, and non-destructive assessment of plant N status and may provide real-time information to support N management decisions in coffee fields. The objective of this study was to evaluate the relationship between laboratory-determined leaf N concentration and chlorophyll meter readings in Coffea arabica (L.) plantations by fitting regression models and comparing predicted and observed values. To generate the main dataset, leaf sampling and chlorophyll measurements were conducted in 153 commercial coffee fields and 62 plots from field trials across the main coffee-producing regions of Minas Gerais and São Paulo states. Composite leaf samples (100 leaves each) were collected per field, measured with the chlorophyll meter, and sent to laboratory for N concentration determination. Data from fields cultivated with the cultivar Catucaí Amarelo 24/137 were used for model calibration, based on the relationship between chlorophyll readings and leaf N concentration. Data from all other fields were used for model validation, assessing both the correlation between predicted and observed values and the classification accuracy of the model in categorizing leaf N levels as Low (≤25 g kg^{-1}), Adequate (>25 and ≤30 g kg^{-1}), or High (>30 g kg^{-1}). A simple linear model was selected for calibration,

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resulting in a coefficient of determination (R^2) of 0.72. However, the comparison between predicted and observed values for the model validation resulted in a lower R^2 due to the narrow range of the dataset, as most samples were between 27.7 and 35.7 g kg $^{-1}$ and only three samples represented low N levels. Despite this limitation, the model demonstrated high classification accuracy, correctly predicting the leaf N level of 77% of the samples. Overall, the results demonstrate that chlorophyll meter readings can be effectively used as a rapid and reliable diagnostic tool to support N management decisions in coffee fields, contributing to improved N use efficiency and reduced environmental impacts.

Keywords.
Nitrogen management; Chlorophyll meter; Coffee arabica; Nitrogen use efficiency.

Introduction

The coffee crop is the third largest consumer of nitrogen (N) in Brazil, after corn and sugarcane, and among the major crops it presents one of the lowest N use efficiencies, based on the ratio of N applied to the N removed by harvest (Cunha et al., 2023). The recommended N application rates based on guidelines from established Brazilian institutions range from 80 to 450 kg ha^{-1} for expected yields between 1,200 and 4,800 kg ha^{-1}, respectively (Guimarães et al., 1999; Quaggio et al., 2022). In practice, N rates applied to coffee fields may exceed these recommendations, which are already high compared to other crops, as overapplication is often used as insurance against uncertainty regarding crop demand. However, this practice is difficult to justify as it reduces economic returns, disrupts plant nutrient balance, increases susceptibility to diseases and contributes to environmental issues (Sadeghian-Khalajabadi et al., 2022). In addition, N fertilizers contribute substantially to agricultural greenhouse gas emissions, mainly through soil N_2O release and upstream production emissions, reinforcing the need for strategies that improve N use efficiency (Menegat et al., 2022). Therefore, accurately predicting N requirements for coffee is essential to reduce uncertainty in N management and enhance both economic and environmental outcomes.

Soil analysis is widely used to assess nutrient availability and guide fertilization practices. However, under tropical conditions, soil N measurements are unreliable indicators of plant-available N due to rapid fluctuations driven by microbial activity and environmental factors (Cantarella & Mattos Jr., 2022). Laboratory-based leaf analysis is the conventional method for monitoring plant N status. This method involves leaf sampling in the field followed by laboratory determination of N concentration. The N concentration in coffee leaves is, in fact, one of the parameters used to guide N recommendations in coffee production in Minas Gerais and São Paulo states, where lower N rates are recommended when leaf N is high and higher rates when it is low (CONAB, 2025; Quaggio et al., 2022; Ribeiro et al., 1999). However, this method is costly and time-consuming, often requiring several days to deliver results, which limits its adoption by farmers and constrains timely decision-making.

To overcome these limitations, several non-destructive sensing approaches have been developed to rapidly estimate plant N status, including reflectance sensors, flavonol meters, and chlorophyll meters (Padilla et al., 2018; Samborski et al., 2009). These methods do not directly measure N concentration but instead infer plant N status from optical indices or indirect measurements of compounds sensitive to N availability, most of which are strongly influenced by leaf chlorophyll content (Padilla et al., 2018). As N is a structural component of chlorophyll molecules, leaf greenness is strongly associated with leaf N concentration (Lambers et al., 2008).

Handheld chlorophyll meters are an established tool for estimating plant N status on several crops and a promise for coffee plants, offering rapid, in-field, and user-friendly measurements that can be readily integrated into fertilization decision-making. Among the most widely used devices are the SPAD-502 (Konica Minolta, Inc., Japan) and the Yara N-Tester™ (Yara International ASA, Norway) (Chakwizira et al., 2020; Gianquinto et al., 2004; Ortuzar-Iragorri et al., 2005; Padilla et al., 2018; Samborski et al., 2009). Studies in Brazil consistently report strong correlations between

SPAD readings and chlorophyll concentration in both arabica and robusta coffee, with coefficients of determination (R^2) ranging from 0.88 to 0.96 (França & Carvalho, 2017; Reis et al., 2009; Torres Netto et al., 2005). Likewise, significant linear relationships between chlorophyll meter values and N concentration in coffee leaves have been observed (Reis et al., 2006; Reis et al., 2009; Torres Netto et al., 2005). Chlorophyll meters have also been shown to support the assessment of crop N responsiveness and to guide fertilization rates to coffee, which tend to decrease as chlorophyll meter values increase (Godoy et al., 2008; Morasi et al., 2015; Reis et al., 2006). In addition, these handheld tools enable early detection of plant N status, facilitating more efficient N management (Reis et al., 2009).

Despite the evidence from previous studies, chlorophyll meters are not yet widely adopted for N management in coffee plantations. Their limited adoption may be attributed to challenges in knowledge transfer, restricted access to technology and the lack of robust calibrations that cover a broad range of regions and account for variability among cultivars. Cultivar-specific traits, such as leaf thickness, chlorophyll distribution, and differences in wax coating on leaves, affect leaf optical properties and, consequently, chlorophyll meter values (Padilla et al., 2018; Torres-Dorante et al., 2016). França & Carvalho (2017) demonstrated that the relationship between leaf N concentration and chlorophyll meter values varies among arabica cultivars. Currently, 125 arabica coffee cultivars are officially registered in Brazil (MAPA, 2026), highlighting the challenge of developing broadly applicable prediction models. While cultivar-specific calibration improves accuracy, it is labor-intensive and limits scalability. An alternative approach to deal with this issue is the use of correction factors, also referred to as variety correction factors, to account for cultivar-related differences and enable the application of generalized prediction models (Torres-Dorante et al., 2016).

Therefore, to address this challenge, a field study was conducted to test the hypothesis that chlorophyll meters can provide a rapid and reliable diagnosis of plant N status across a wide range of regions and arabica coffee cultivars. The objective was to evaluate the relationship between leaf N concentration and chlorophyll meter values, as well as the accuracy of predicted N levels using N-Tester measurements combined with variety correction factors across major coffee-producing regions in Brazil and multiple cultivars.

Materials and methods

The field study was conducted during two growing seasons (2024/2025 and 2025/2026). A total of 153 commercial arabica coffee production fields and 62 plots from research trials were selected for leaf sampling and chlorophyll meter readings, resulting in 215 sampling sites. Commercial fields were selected from farmers with a strong history of good crop management practices to avoid areas with nutritional deficiencies or other confounding factors that could negatively affect the correlation between leaf N concentration and chlorophyll meter readings. The field data were collected from 24 municipalities across the states of Minas Gerais and São Paulo, comprising 63, 41, 93, and 18 samples from the Sul de Minas, Matas de Minas, Cerrado and Mogiana Paulista regions, respectively (Fig. 1). Plant age varied among fields, ranging from 2 to 35 years, and a total of 52 different cultivars were evaluated.

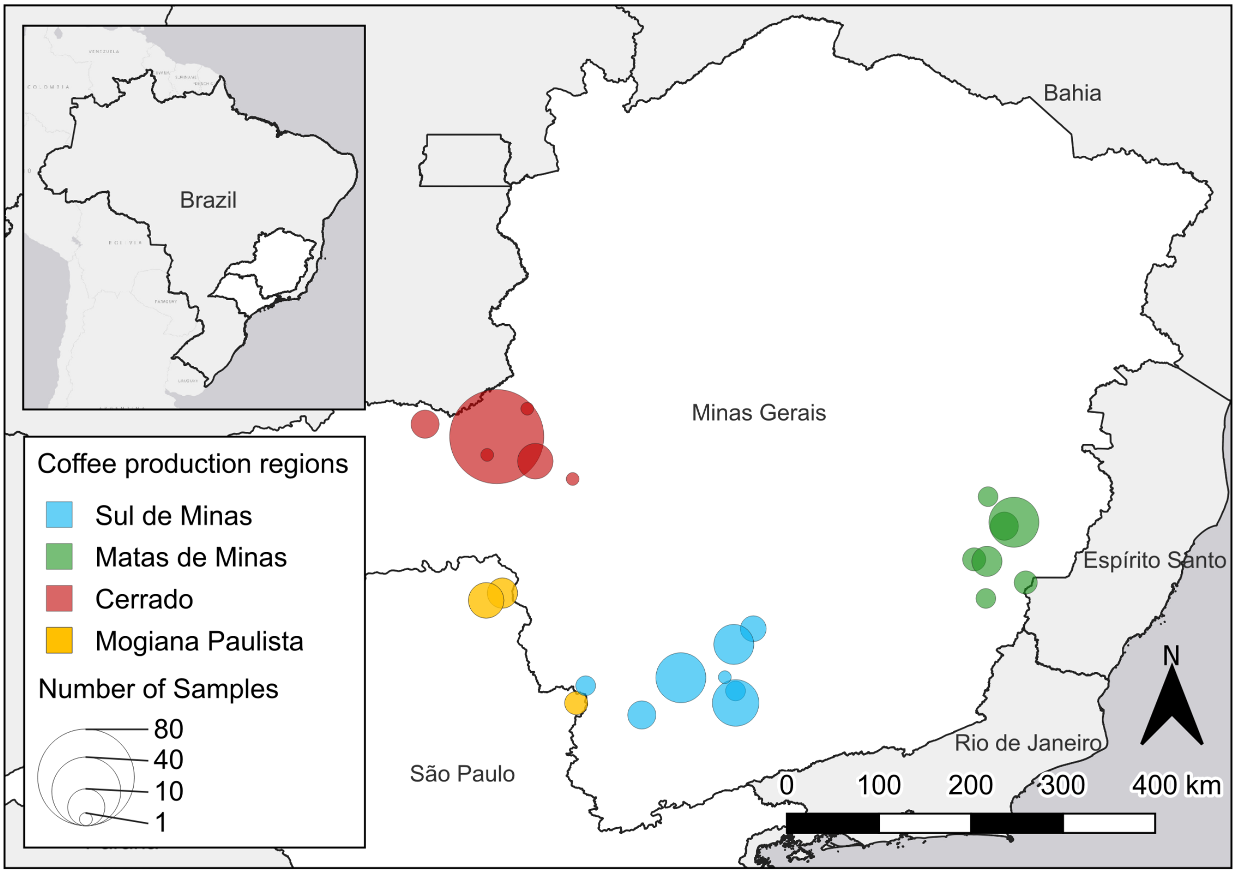

Fig. 1 Range-graded proportional circle maps of sampling sites in arabica coffee fields in different coffee production regions in Brazil. The area of each circle denotes the number of samples on each site.

Leaf sampling was performed according to Guimarães et al. (1999). Composite samples were obtained from the third pair of leaves from the apex of fruit-bearing branches located in the middle third of the plant canopy, on both sides of the rows. Samples were collected from 25 plants per field, with four leaves per plant, resulting in a composite sample of 100 leaves. Sampling was carried out at the beginning of fruit expansion, at least 30 days after N fertilization. Plants with abnormal appearance, leaves showing insect or disease damage, and leaves contaminated with soil or dust were not sampled.

The same leaves collected for chemical analysis were measured *in situ* using a chlorophyll meter at the time of sampling. One reading was taken per leaf, resulting in 100 measurements per field. Measurements were performed midway between the petiole and the leaf tip, and between the midrib and the leaf margin. After sampling, leaves were sent to the laboratory, oven-dried, ground, and analyzed for macro- and micronutrient concentrations (N, P, K, Ca, Mg, S, B, Cu, Fe, Mn, and Zn). Leaf N concentration was classified into three categories: Low ($\leq$25 g kg^{-1}), Adequate (>25 and $\leq$30 g kg^{-1}), and High (>30 g kg^{-1}), according to Quaggio et al. (2022).

The chlorophyll meter used was the Yara N-Tester™ BT, which connects to a smartphone via Bluetooth as user interface. Measurements are based on leaf light transmittance at two wavelengths, approximately 650 and 960 nm. Data from each measurement were transmitted to a smartphone application, which calculated chlorophyll meter values and uploaded the data to a cloud server database, including timestamp and geolocation information.

Data from fields cultivated with the cultivar Catucaí Amarelo 24/137 were used to develop the correlation curve between chlorophyll meter readings and leaf N concentration. The statistical data normality was evaluated using the Shapiro–Wilk test ($p > 0.05$). Regression analysis was then performed between chlorophyll meter values and leaf N concentration, fitting both linear and quadratic models. All regression analyses were performed using SigmaPlot software (version 14.0; Systat Software Inc.). Data from the remaining cultivars were used to evaluate the predictive performance of the selected regression model.

After selecting Catucaí Amarelo 24/137 as the model reference cultivar, chlorophyll meter values from the remaining cultivars were adjusted by adding or subtracting the difference between their mean values and that of the reference cultivar, a process called variety correction. This variety correction was applied prior to model validation following the approach described by Torres-Dorante et al. (2016), allowing alignment of cultivar-specific chlorophyll meter scales to a common reference. This procedure accounts for systematic differences in leaf optical properties among cultivars while preserving the underlying relationship between chlorophyll meter values and leaf N concentration. The validation of the prediction model was assessed according to coefficient of determination (R^2), root mean square error (RMSE) and the ratio of performance to deviation (RPD).

Classification performance of the prediction model was evaluated using two complementary metrics: sample-level accuracy (% validity) (Eq. 1) and distribution-level agreement (% proportion accuracy) (Eq. 2) (Widjaja Putra and Soni, 2018). Validity of the model was defined as the proportion of correctly classified samples, obtained by comparing predicted classifications with laboratory reference classes:

$$\text{Validity (\%)} = \frac{\sum \text{Nclass}_{(\text{correctly predicted})}}{\text{Total sample}} \times 100 \quad (1)$$

where: $\sum \text{Nclass}_{(\text{correctly predicted})}$ is obtained from the sum of $\text{Nclass}_{(\text{correctly predicted})}$ which represents the number of times the value ‘1’ is assigned using the following logic: if $\text{Nclass}_{(\text{predicted})} = \text{Nclass}_{(\text{observed})}$, then $\text{Nclass}_{(\text{correctly predicted})} = 1$; otherwise, $\text{Nclass}_{(\text{correctly predicted})} = 0$.

Proportion accuracy of the model was calculated as:

$$\text{Proportion accuracy (\%)} = \frac{\sum \text{Nclass} \min\left(\text{Nclass}_{(\text{observed})}, \text{Nclass}_{(\text{predicted})}\right)}{\text{Total sample}} \times 100 \quad (2)$$

where $\text{Nclass}_{(\text{observed})}$ and $\text{Nclass}_{(\text{predicted})}$ represent the number of samples assigned to each class based on laboratory measurements and model predictions, respectively. This metric represents the normalized overlap between class distributions, in which the minimum count per class corresponds to the maximum possible agreement. Thus, validity reflects sample-wise classification accuracy, whereas proportion accuracy evaluates the ability of the model to reproduce the overall distribution of N status classes, independently of individual sample agreement.

Results and discussion

Arabica coffee production in the Sul de Minas, Matas de Minas, Cerrado, and Mogiana Paulista regions accounts for 37, 23, 14, and 14%, respectively, of the total production area in Brazil (CONAB, 2025). In the present study, the proportion of samples collected from these regions was 29, 19, 43, and 8%, respectively (Fig. 1). Although a higher proportion of samples was obtained from the Cerrado region, efforts were made to approximate the representativeness of each region. The greater number of samples from the Cerrado region was partly due to sampling conducted in a cultivar demonstration trial, where 20 cultivars were evaluated.

The collected leaf samples classified as having high N levels (>30 g kg^{-1}) were predominant, representing 75% of the dataset. Only 1% of samples were classified as low (≤25 g kg^{-1}), while 24% were considered adequate (>25 and ≤30 g kg^{-1}). Half of the samples had N concentrations between 29.9 and 33.0 g kg^{-1}, corresponding to the first and third quartiles, respectively (Fig. 2).

These results indicate that N oversupply in coffee fields is leading to the accumulation of N in plant tissues above levels considered adequate for optimal development, which has important effects. Nutrient imbalance in plants due to excessive N application may negatively affect yield (Assis et al., 2015), reduce cup quality due to alterations in the N:K ratio in coffee beans (Clemente et al., 2015), increase susceptibility to pests such as the coffee berry borer (*Hypothenemus hampei* Ferr.) (Dwomoh et al., 2018) and favor the incidence of Phoma spot disease in arabica coffee plants (*Phoma tarda* R.B. Stewart) (Lima et al., 2010).

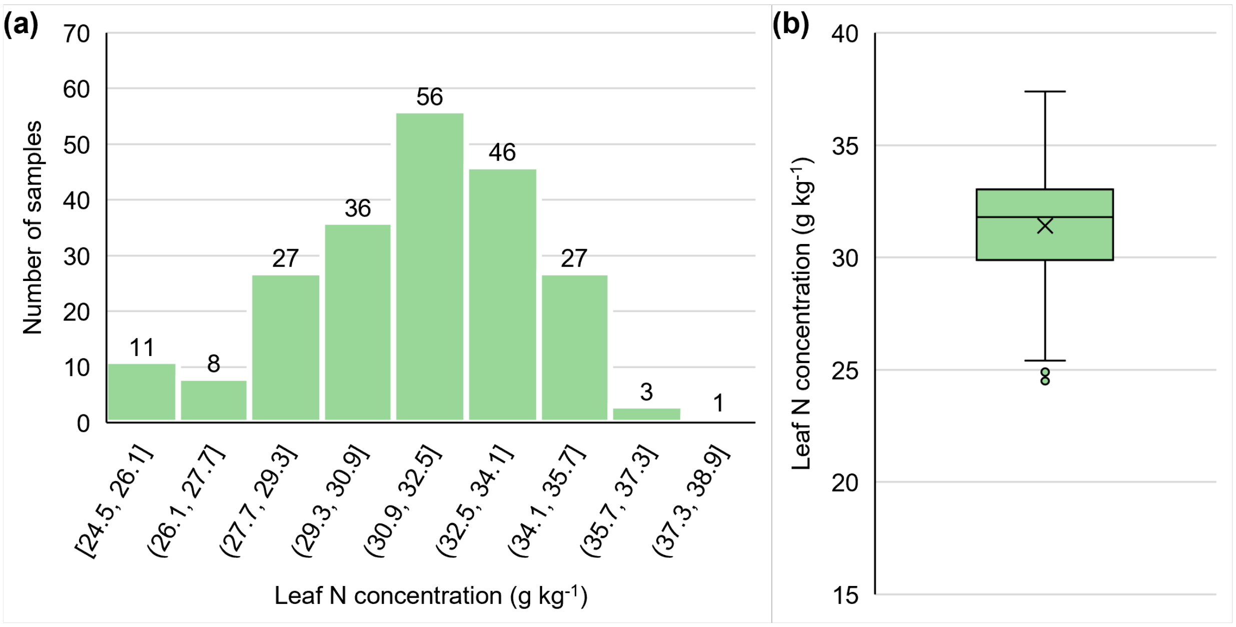

Fig. 2 Distribution (a) and boxplot (b) of leaf N concentration observed in the laboratory (215 samples). In the boxplots, the whiskers indicate the minimum and maximum value. The top of the box represents the 1st quartile, and the bottom of the box represents the 3rd quartile. The horizontal line inside the box represents the median. Mean values are represented by an X. The points that fall outside the whiskers are considered outliers.

The average N-Tester value was 890 (Fig. 3), which is considerably higher than values reported for other crop types. For instance, Torres-Dorante et al. (2016) reported maximum values of approximately 700 units in corn, while Chakwizira et al. (2020) identified critical N levels in wheat corresponding to values between 530 and 620 units. In potato, N-Tester values are typically below 650 units (Gianquinto et al., 2004). It is important to note that chlorophyll meter values are dimensionless. Although the measurement principle of the N-Tester is similar to that of the SPAD-502, values are expressed on different scales, that is why the 3-digit or 4-digit values are commonly observed in N-Tester readings, while 2-digit values are commonly observed in SPAD readings.

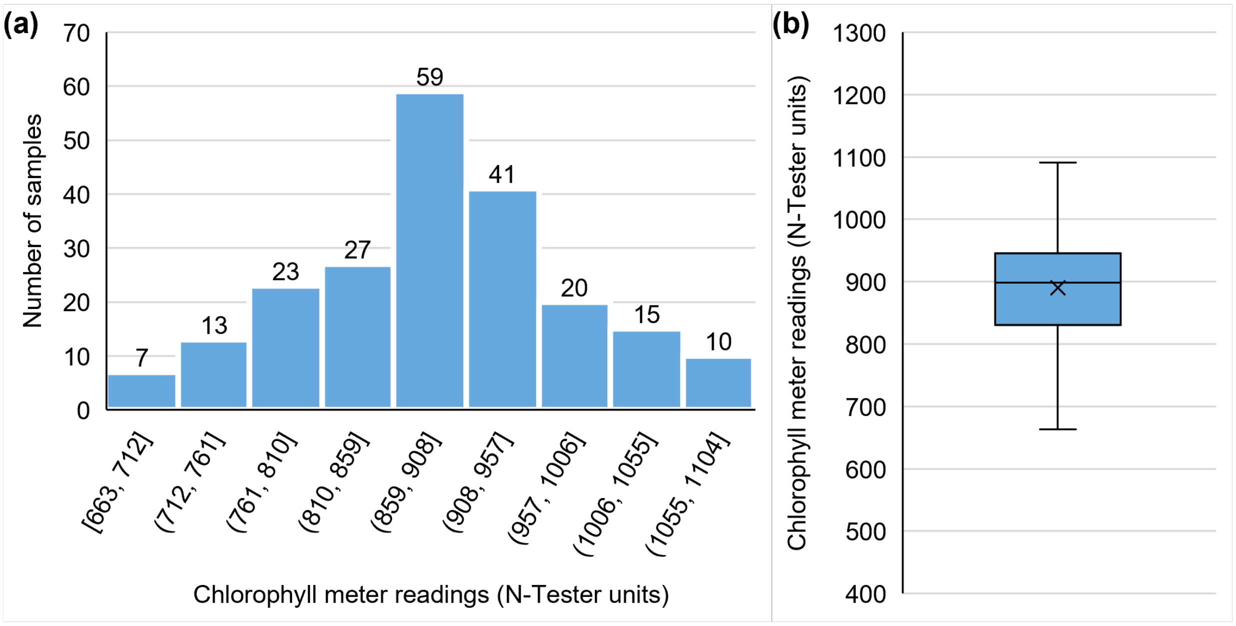

Fig. 3 Distribution (a) and boxplot (b) of chlorophyll meter readings (215 samples). In the boxplots, the whiskers indicate the minimum and maximum value. The top of the box represents the 1st quartile, and the bottom of the box represents the 3rd quartile. The horizontal line inside the box represents the median. Mean values are represented by an X.

Model calibration

The most sampled cultivars were "Catucaí Vermelho IAC 144", "IPR 100", and "Catucaí Amarelo 24/137", with 25, 20, and 17 samples, respectively. Despite the smaller number of samples, Catucaí Amarelo 24/137 was selected for the calibration model because it exhibited a wider range of chlorophyll meter values and leaf N concentrations compared to the other cultivars, which is advantageous for a robust model fitting.

The analysis of variance revealed that both linear and quadratic models provided a significant fit, each with an R^2 of 0.72 (Table 1). The linear model was selected to predict leaf N concentration from chlorophyll meter values due to its simpler interpretation and consistent behavior with established relationships in coffee. As observed in previous studies with coffee plants, chlorophyll meter values and leaf N concentration have a positive linear correlation (Reis et al., 2006; Reis et al., 2009; Torres Netto et al., 2005). This relationship depends on several factors, such as growth stage and measurement methodology. Morasi et al. (2015) reported substantial variation in chlorophyll meter values throughout the coffee growth cycle, with approximately a 50% increase from December, when N fertilization begins, to a maximum in July, during harvest. According to Godoy et al. (2008), significant correlations are observed from the fruit expansion stage onward, but not immediately after flowering. In the present study, chlorophyll meter measurements were taken at the same growth stage used for leaf sampling and at the same leaf position, following validated protocols for arabica coffee for which critical levels are well established (Guimarães et al., 1999; Quaggio et al., 2022).

Wicharucka et al. (2024), working specifically with arabica coffee, reported a negative linear correlation ($R^2 = 0.63$) between chlorophyll meter values and leaf N concentration when sampling leaves from the upper canopy. This contrasts with the positive relationships observed in the present study and in several other studies across different species, where chlorophyll meter values increase with leaf N concentration (Gianquinto et al., 2004; Ortuzar-Iragorri et al., 2005; Torres-Dorante et al., 2016). The observed discrepancy is likely related to differences in sampling position within the canopy, as Reis et al. (2006) reported that the middle canopy provides more reliable estimates of plant N status than the upper canopy in coffee plants. The observed discrepancy may also be associated with differences in growth stage at the time of sampling.

Table 1. Analysis of variance for polynomial regressions models for the correlation between leaf nitrogen concentration and chlorophyll meter reading, including degree of freedom (DF), sum of squares (SS), median square (MS), test F, *p*-value, and respective coefficient of determination (R^2).

Model	Source	DF	SS	MS	F	*p*-value	R^2
Linear	Regression	1	35.4591	35.4591	36.6168	<0.0001	0.72
	Residual	15	14.5257	0.9684			
	Total	16	49.9848	3.1241			
Quadratic	Regression	2	35.5706	17.7853	17.2741	0.0002	0.72
	Residual	14	14.4143	1.0296			
	Total	16	49.9848	3.1241			

With the objective of extending the calibration developed for Catucaí Amarelo 24/137, variety correction was applied to the remaining cultivars. Before the variety correction, average chlorophyll meter values ranged from 666 units for cultivar IPR 99 to 889 units for Mundo Novo IAC 379 – 19, both with the same average leaf N concentration (32 g kg^{-1}), indicating substantial variation among cultivars. This variability reflects inherent differences in leaf greenness and optical properties associated with each cultivar. If not accounted for, such differences may introduce systematic bias in model predictions, leading to underestimation of leaf N concentration in cultivars with lower chlorophyll meter values (e.g., IPR 99) and overestimation in cultivars with higher values (e.g., Mundo Novo IAC 379 – 19).

Model performance assessment

Since 17 samples were used in present study to develop the prediction model (model data), the remaining 198 samples were used to assess the performance of the model (test data). A low R^2 (0.14) was obtained in the comparison of predicted leaf N concentration and observed leaf N concentration (Fig. 4). However, this low coefficient of determination should be interpreted in the context of the limited range of the dataset rather than as evidence of an inherently weak relationship. In the present study, observed values from the laboratory are mostly confined between 27.7 and 35.7 units (Fig. 2), resulting in a restricted overall variance of the response variable. Under such conditions, even modest absolute prediction errors can represent a substantial fraction of the total variance, which intrinsically limits attainable R^2 values. This phenomenon is well recognized in regression and chemometric modeling, where R^2 is known to depend strongly on the variance structure of the dataset and not solely on the strength of the underlying relationship (Geladi & Kowalski, 1986). In the present case, the linear model yielded an RMSE of approximately 2.46 units (Fig. 4), which is small in absolute terms but non-negligible relative to the total spread of predicted values, leading to an R^2 of 0.14. A similar conclusion is supported by the ratio of performance to deviation (RPD 1.08), indicating that predictive performance is constrained primarily by the narrow data range rather than by random model inadequacy. Previous studies have emphasized that low R^2 values are expected in datasets with limited variability and homogeneous samples, and that RMSE-based metrics and residual analysis often provide a more meaningful evaluation of model performance in such cases (Fearn, 2002). Consequently, reliance on R^2 alone may lead to an underestimation of model relevance.

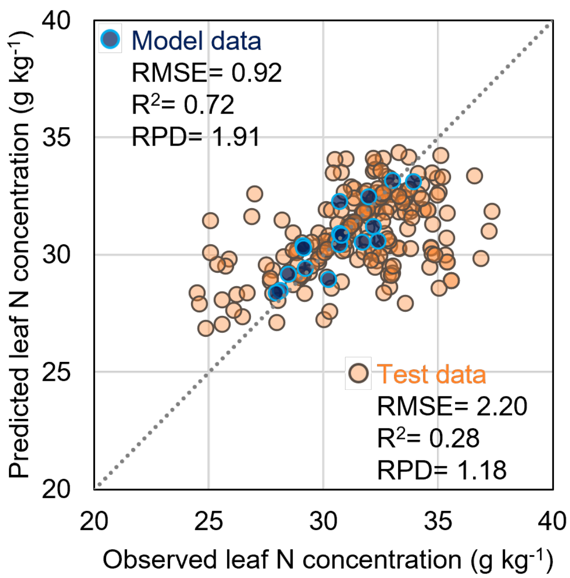

Fig. 4 Scatter plot comparing predicted leaf N concentration by using chlorophyll meter and observed leaf N concentration from laboratory analysis (198 samples used to test the prediction model and 17 samples used to build the prediction model). The dotted line represents the 1:1 relationship.

Because N fertilization recommendations in coffee are based on leaf N status classes rather than precise continuous values (Guimarães et al., 1999; Quaggio et al., 2022), classification performance provides a more directly relevant evaluation of model applicability than regression-based metrics alone. In this context, the ability of the model to correctly assign samples to agronomic N categories is more relevant than small deviations in predicted leaf N concentration. Therefore, the objective of the prediction model is not precise prediction of leaf N concentration, but reliable classification of plant N status for fertilization decision support. The validity accuracy obtained in the present study was 77% (Table 2), indicating that 77% of the samples were correctly classified. The proportion accuracy of 96% (Table 2) indicates that the model accurately reproduces the overall distribution of N status classes. Widjaja Putra and Soni (2018) reported validity and proportion accuracy values of 68.3% and 86%, respectively, when evaluating chlorophyll meter estimates of leaf N status in robusta coffee under a single cultivar and location. In that study, other remote sensing approaches based on vegetation indices from spectrometers and digital cameras were also tested, but none outperformed chlorophyll meters in classification performance.

Table 2. Performance evaluation of the prediction model in estimation of nitrogen class in coffee leaves (198 samples).

Classification performance	Samples with different nitrogen class (n)			Accuracy (%)	
	Low	Adequate	High	Validity	Proportion
Observed	3	45	150		
Predicted	0	60	138	77.3	96.5

Considering that a classification accuracy of 77% was achieved across 52 cultivars and 198 sampling sites (Table 2), the current model shows consistent performance. The observed results indicate potential for supporting N management decisions in coffee production systems by enabling rapid estimation of leaf N status and contributing to improved fertilization decisions with reduced risk of N overapplication. However, certain limitations must be considered. Chlorophyll meter values are influenced by factors beyond cultivar and measurement methodology, including water stress and deficiencies of nutrients other than N (Samborski et al., 2018). Therefore, their use is recommended in well-managed fields without significant nutritional imbalances and primarily for fine-tuning N fertilization. In addition, chlorophyll meters cannot replace full leaf analysis covering macro- and micronutrients, as their relationship with other nutrients is generally weak (Zanella et al., 2020), and they should instead be considered a complementary tool for rapid assessment of plant N status.

Conclusion

The chlorophyll meter can be integrated into the decision-making processes of N management in coffee plantations. The results indicate that its application is not restricted to a limited number of cultivars or regions, and it can be used across a broad range of coffee production systems. Continuous evaluation, including new cultivars, may further improve the calibration robustness. The present study demonstrates satisfactory accuracy of N-Tester chlorophyll meter for predicting N status across 52 cultivars in 24 municipalities within the main coffee-producing regions of Brazil. This represents an important step toward overcoming the limitations of conventional leaf analysis by providing timely and in-field information to support N management decisions.

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