

Postprint: Comparison of Nitrate Reflectometer and SPAD Method for Maize Nitrogen Nutrition Diagnosis

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Abstract

Precise nutritional diagnosis is the basis for understanding crop nitrogen nutrition and making fertilizer recommendations. This study investigated nitrogen nutrition diagnosis at key growth stages of corn using two diagnostic methods—the SPAD chlorophyll meter (SPAD-502 Plus) and the nitrate reflectometer (RQ flex10)—under field drip irrigation conditions, aiming to select an appropriate diagnostic method and establish fertilization models for different growth stages of drip-irrigated corn based on diagnostic values. The experiment was conducted with five nitrogen application rates: 0 kg(N) · hm² (N0), 225 kg(N) · hm² (N225), 330 kg(N) · hm² (N330), 435 kg(N) · hm² (N435), and 540 kg(N) · hm² (N540). At different growth stages, corn leaf SPAD values and leaf sheath NO₃ content were measured and regressed against nitrogen application rate, plant total nitrogen content, and yield to compare the responses of the two diagnostic methods to corn nitrogen nutrition. The results showed that: 1) Both corn leaf SPAD values and leaf sheath NO₃ content increased significantly with increasing nitrogen application rate, with the most sensitive response occurring at the jointing stage. Leaf sheath NO₃ content showed a greater response to changes in nitrogen application rate than SPAD values, and its goodness of fit with nitrogen application rate and corn yield was higher than that of SPAD values, indicating that the nitrate reflectometer method is more sensitive in reflecting nitrogen sufficiency or deficiency in drip-irrigated corn. 2) Corn total nitrogen content showed a significant linear relationship with leaf SPAD values, while it was represented by a linear-plus-plateau model with leaf sheath NO₃ content. When leaf sheath NO₃ content was less than 186 mg · L⁻¹, plant total nitrogen was significantly linearly correlated with NO₃; when leaf sheath NO₃ content exceeded 186 mg · L⁻¹, plant total nitrogen tended to remain unchanged with increasing NO₃ content. 3) The optimal economic nitrogen application rate for drip-irrigated corn in this agricultural region was 402.5 kg · hm², with a corresponding corn yield of 17 049 kg · hm². The critical leaf sheath NO₃

contents at the jointing, tasseling and silking, and grain filling stages were 729.3 mg·L⁻¹, 536 mg·L⁻¹, and 81.2 mg·L⁻¹, respectively. Both the SPAD chlorophyll meter and nitrate reflectometer can be used for nitrogen nutrition diagnosis in drip-irrigated corn; however, nitrate rapid test values can more sensitively reflect nitrogen sufficiency or deficiency status, and nitrogen nutrition diagnosis and fertilizer recommendation based on the nitrate reflectance method exhibit good accuracy and applicability.

Full Text

Abstract

Precise and prompt crop nutrient diagnosis is a prerequisite for determining crop nitrogen content and recommending reasonable nitrogen fertilizer application rates. This study investigated nitrogen nutrition diagnosis in maize during key growth stages under field drip irrigation conditions using two diagnostic methods: the SPAD chlorophyll meter (SPAD-502 Plus) and nitrate reflectometer (RQ flex10). The objective was to identify the most suitable diagnostic method and establish a fertilization model for drip-irrigated maize at different growth stages. Five nitrogen application rates were arranged: 0 kg(N)·hm⁻² (N0), 225 kg(N)·hm⁻² (N225), 330 kg(N)·hm⁻² (N330), 435 kg(N)·hm⁻² (N435), and 540 kg(N)·hm⁻² (N540). Leaf SPAD values and leaf sheath NO₃⁻ content were measured at different growth stages and fitted against nitrogen application rate, plant total nitrogen content, and yield to compare the responses of the two diagnostic methods to maize nitrogen nutrition. The results showed: (1) Both maize leaf SPAD values and leaf sheath NO₃⁻ content increased significantly with increasing nitrogen application rate, with the most sensitive response occurring at the jointing stage. Leaf sheath NO₃⁻ content showed greater sensitivity to nitrogen application changes than SPAD values, and demonstrated higher fitting degrees with both nitrogen application rate and maize yield, indicating that the nitrate reflectometer method is more responsive to nitrogen abundance or deficiency in drip-irrigated maize. (2) Maize total nitrogen content showed a significant linear relationship with leaf SPAD values, while it exhibited a linear-plus-plateau relationship with leaf sheath NO₃⁻ content. When leaf sheath NO₃⁻ content was below 186 mg·L⁻¹, plant total nitrogen increased linearly with NO₃⁻ content; however, when NO₃⁻ content exceeded 186 mg·L⁻¹, plant total nitrogen remained relatively stable despite further increases in NO₃⁻ content. (3) The optimal economic nitrogen application rate for drip-irrigated maize in this agricultural region was 402.5 kg·hm⁻², corresponding to a maize yield of 17,049 kg·hm⁻². The critical leaf sheath NO₃⁻ concentrations at the jointing, tasseling-silking, and grain-filling stages were 729.3 mg·L⁻¹, 536 mg·L⁻¹, and 81.2 mg·L⁻¹, respectively. Both SPAD chlorophyll meter and nitrate reflectometer can be used for nitrogen nutrition diagnosis in drip-irrigated maize, but nitrate rapid test values can more sensitively reflect nitrogen status. The nitrate reflectometer method demonstrates good accuracy and applicability for crop nitrogen nutrition diagnosis and fertil-

izer recommendation.

Keywords: nitrogen application rate; maize; nitrogen nutrition; nitrate reflectometer; chlorophyll meter; SPAD reading; sheath NO_3^- concentration; nutrient diagnosis

Introduction

Crop nutrient diagnosis is a comprehensive technology that accurately obtains crop nutritional status at specific growth stages through simple and rapid means, providing a basis for diagnosis and fertilizer recommendations. Although plant total nitrogen can effectively reflect crop nitrogen nutrition and is closely correlated with crop yield [1], its determination involves complex chemical analysis, is time-consuming, and requires high technical skills. Modern agriculture demands precise, rapid, and convenient simplified diagnostic techniques for crop nitrogen nutrition. In recent years, the SPAD chlorophyll meter, nitrate reflectometer, and Greenseeker remote sensing spectrometer have been gradually applied to crop nitrogen nutrition diagnosis [2]. Dang Ruijuan et al. [3] confirmed that SPAD values of different leaf layers in summer maize (*Zea mays*) were significantly correlated with nitrogen content, and that measuring leaf chlorophyll content could reveal crop nitrogen status and further predict crop yield [4]. Chen Xiaoqun et al. [5] utilized the chlorophyll meter method for field nitrogen management in rice (*Oryza sativa*). Hu Hao et al. [6] attempted to estimate winter wheat (*Triticum aestivum*) yield through SPAD values and NDVI values. Both Piekkielek et al. [7] and Francis et al. [8] reported using chlorophyll meters to predict crop nitrogen topdressing rates and provide fertilization guidance. Nitrate nitrogen is a sensitive indicator reflecting nitrogen status in dryland crops. Papastylianou et al. [9] studied using NO_3^- measured by nitrate reflectometer as a nitrogen nutrition diagnostic indicator, suggesting that this method could estimate plant nitrogen status and recommend topdressing.

China initially established a nitrate diagnostic and topdressing technical system for wheat and maize in the late 20th century [10]. Wang Xiaojing et al. [11] used a reflectometer to measure cotton (*Gossypium* sp.) petiole nitrate concentration for plant nitrogen nutrition diagnosis and fertilization guidance. Although the chlorophyll meter offers advantages of simple operation and rapid data acquisition, SPAD readings are significantly affected by light radiation [12], and the method requires measuring multiple plants and using the average value as the result, which involves substantial workload [13]. Guo Jianhua et al. [14] suggested that although NO_3^- content in crop tissues can sensitively reflect crop nitrogen status, measurement results become unstable when NO_3^- content is high in plant tissues. These findings indicate that different nitrogen diagnostic methods have specific applicability and limitations, making it crucial to select appropriate diagnostic methods for crops in agricultural production. Previous research on nitrogen diagnostic technology has primarily focused on the application of single diagnostic techniques in crop nutrition diagnosis and fertilization, with few studies systematically comparing the accuracy and applicability of dif-

ferent diagnostic technologies for crop nitrogen diagnosis. This study aims to identify optimal nitrogen diagnostic methods for maize and provide fertilization recommendations accordingly.

The oasis on the northern slope of the Tianshan Mountains is an important water-saving drip irrigation agricultural region in Xinjiang. Under the integrated water and fertilizer management model of drip irrigation, nitrogen topdressing typically accounts for over 80% of total nitrogen application, applied 5–7 times through drip irrigation at different growth stages to meet crop nitrogen demands [15–16]. Under this fertilization model, timely and accurate diagnosis of crop nitrogen nutrition at different growth stages is a prerequisite for determining the recommended amount for each topdressing application. Therefore, this study compared the application effects of chlorophyll meter and nitrate reflectometer methods in nitrogen nutrition diagnosis of drip-irrigated maize, aiming to identify a suitable nitrogen nutrition diagnostic method and provide a basis for precise nitrogen topdressing at different maize growth stages.

1.1 Study Site Overview

The experiment was conducted in 2013 at the Wulanwusu Agro-meteorological Experiment Station in Shawan County, Xinjiang (44°17 N, 85°51 E). The station is located at an average elevation of 450 m with an average annual rainfall of approximately 187.7 mm. The experimental area soil type was irrigated gray desert soil (Calcaric Fluvisol) with a loam texture. The topsoil layer (0–20 cm) had a pH of 8.52, organic matter content of 18.73 g · kg⁻¹, total nitrogen of 0.96 g · kg⁻¹, available phosphorus of 23.87 mg · kg⁻¹, and available potassium of 340.95 mg · kg⁻¹. The test crop was maize cultivar ‘Liangyu 66’ (Zea mays cv. Liangyu 66), a spring maize variety.

1.2 Field Experimental Design

A drip irrigation plot experiment was conducted with five nitrogen application rates: 0 kg(N) · hm⁻² (N0), 225 kg(N) · hm⁻² (N225), 330 kg(N) · hm⁻² (N330), 435 kg(N) · hm⁻² (N435), and 540 kg(N) · hm⁻² (N540). The experiment included three replicates, totaling 15 plots arranged in a randomized block design. Nitrogen fertilizer was urea (N ≥ 46.6%), phosphorus fertilizer was monoammonium phosphate (N ≥ 12%, P₂O₅ ≥ 61%), and potassium fertilizer was potassium sulfate (K₂O ≥ 51%).

Sowing was conducted on April 27–28, with emergence on May 5–6. The planting pattern used wide-narrow row film mulching (40 cm + 80 cm), with a film width of 70 cm, film spacing of 60 cm, and plant spacing of 14.5 cm. Each film accommodated two rows of maize with one drip irrigation line, resulting in a planting density of 114,945 plants · hm⁻². Each plot contained four films, with a plot area of 38.4 m² (4.8 m × 8.0 m). The total irrigation amount during the growth period was 6,750 m³ · hm⁻². Phosphorus application rate was 90 kg(P₂O₅) · hm⁻² and potassium application rate was 90 kg(K₂O) · hm⁻².

All nitrogen, phosphorus, and potassium fertilizers were applied as topdressing through drip irrigation, with 10 irrigation events and 8 fertilization events during the growth period. Field management measures at each growth stage were equivalent to local conventional practices. The distribution proportions of water and fertilizer during different growth stages are shown in Table 1 .

1.3 Measurement Indicators and Methods

Leaf SPAD measurement: Measurements were taken during the jointing stage (big bell mouth stage), tasseling-silking stage, and grain-filling stage on clear, cloudless days between 10:00-12:00 AM. The uppermost fully expanded leaf was measured at the jointing stage, while the ear leaf was measured at the tasseling-silking and grain-filling stages. A chlorophyll meter (SPAD-502Plus, Japan) was used to take measurements at the 1/4, 2/4, and 3/4 positions between the leaf margin and midrib, with the average value recorded. Ten undamaged, uniformly growing plants were randomly selected from each plot for measurement.

Leaf sheath NO_3^- content measurement: Conducted simultaneously with leaf SPAD value measurement between 10:00-12:00 AM, when crop metabolism is in dynamic equilibrium and stored nitrates best reflect the relative relationship between nutrient absorption and assimilation. (1) Sampling: At the jointing stage, the leaf sheath of the uppermost fully expanded leaf was collected; at the tasseling-silking and grain-filling stages, the leaf sheath of the ear leaf was collected. Three undamaged, uniformly growing maize plants were randomly selected from each plot for sampling. (2) Measurement: Samples were measured immediately in the field to avoid changes in plant NO_3^- content. A juicer was used to extract sap from leaf sheaths to obtain test solution. Special test strips were dipped in the solution and measured using a nitrate reflectometer (RQ flex10, Merck, Germany). Each sample was measured three times in parallel, and the average value was recorded. Due to varying NO_3^- concentrations in leaf sheaths at different growth stages, samples within the measurement range could be measured directly, while those exceeding the range required dilution with distilled water before measurement.

Plant total nitrogen determination: Samples were crushed and analyzed using the Kjeldahl method.

Yield determination: At maturity, samples were collected for yield component analysis, and actual plot yields were measured.

1.4 Data Analysis

Data processing and graphing were performed using Microsoft Excel 2013, SPSS 20.0, and GraphPad Prism 5.0 (GraphPad Software, San Diego, USA). One-way ANOVA and LSD multiple comparison tests ($\alpha = 0.05$) were used to analyze significant differences among treatments. Correlation analysis among variables was conducted using all observed values.

2.1 Dynamic Changes in Maize Leaf SPAD Values and Leaf Sheath NO_3^- Content

As shown in Figure 1 [Figure 1: see original paper]A, maize leaf SPAD values (hereinafter referred to as SPAD values) ranged from 45.3 to 56.5. SPAD values increased with maize growth progression and increased with nitrogen application rate at all stages, with the highest values observed under the N540 treatment. SPAD values under all nitrogen treatments were significantly higher than the control (N0) ($P < 0.05$), but no significant differences were observed among N225, N330, and N435 treatments. As shown in Figure 1B, maize leaf sheath NO_3^- content (hereinafter referred to as NO_3^- content) ranged from 17.0 to 886.7 $\text{mg} \cdot \text{L}^{-1}$. NO_3^- content decreased with growth progression, dropping sharply at the grain-filling stage (below 100 $\text{mg} \cdot \text{L}^{-1}$). At all growth stages, leaf sheath NO_3^- content increased with nitrogen application rate, with all nitrogen treatments showing significantly higher NO_3^- content than the control ($P < 0.05$), though no significant difference was observed between N435 and N540 treatments. The response of leaf sheath NO_3^- content to nitrogen application rate was significantly greater than that of SPAD values from jointing to grain-filling stage.

2.2 Response of Maize Leaf SPAD Values and Leaf Sheath NO_3^- Content to Nitrogen Application Rate

At all growth stages, both maize leaf SPAD values and leaf sheath NO_3^- content showed extremely significant linear increases with nitrogen application rate (cumulative nitrogen applied before measurement) (Figure 2 [Figure 2: see original paper]). Based on the distribution of regression equation trend lines and regression coefficients for SPAD values versus nitrogen application rate, the increase in leaf SPAD values with nitrogen application rate at the tasseling-silking and grain-filling stages was significantly smaller than at the jointing stage (Figure 2A), indicating that SPAD values were more responsive to nitrogen supply at the jointing stage. The trend of NO_3^- content changing with nitrogen application rate was similar to that of the chlorophyll meter method (Figure 2B), with the most sensitive response period also occurring at the jointing stage, followed by the tasseling-silking stage, and the smallest response at the grain-filling stage. The increase in leaf sheath NO_3^- content with nitrogen application rate was greater than that of SPAD values at all growth stages, indicating that NO_3^- content can more sensitively reflect maize plant nitrogen nutrition status than SPAD values.

2.3 Relationships Among Maize Leaf SPAD Values, Leaf Sheath NO_3^- Content, and Plant Total Nitrogen Content

As shown in Figure 3 [Figure 3: see original paper], plant total nitrogen content, SPAD values, and NO_3^- content exhibited different functional relationships during the maize jointing to grain-filling stages. Plant total nitrogen content increased with leaf SPAD values, showing an extremely significant linear rela-

tionship (Figure 3A). The relationship between plant total nitrogen and leaf sheath NO_3^- content followed a linear-plus-plateau pattern (Figure 3B). When leaf sheath NO_3^- content was below $186 \text{ mg} \cdot \text{L}^{-1}$, plant total nitrogen content increased linearly with NO_3^- content; however, when leaf sheath NO_3^- content exceeded $186 \text{ mg} \cdot \text{L}^{-1}$, plant total nitrogen remained relatively stable despite further increases in NO_3^- content. Due to the wide range of NO_3^- content variation ($17.0\text{--}886.7 \text{ mg} \cdot \text{L}^{-1}$), plant total nitrogen content showed no significant change when leaf sheath NO_3^- content exceeded $186 \text{ mg} \cdot \text{L}^{-1}$, while NO_3^- content itself changed significantly, indicating that total nitrogen could no longer sensitively reflect maize nitrogen nutrition status at this stage. Additionally, the relationship between maize SPAD values and leaf sheath NO_3^- content could be fitted with both linear-plus-plateau and exponential function models. When leaf sheath NO_3^- content was below $213.2 \text{ mg} \cdot \text{L}^{-1}$, SPAD values increased linearly with NO_3^- content; when NO_3^- content exceeded $213.2 \text{ mg} \cdot \text{L}^{-1}$, SPAD values increased exponentially with NO_3^- content, and unit changes in SPAD values caused significant changes in NO_3^- content (Figure 3D). These results further demonstrate that leaf sheath NO_3^- content can more sensitively reflect maize nitrogen nutrition status than SPAD values.

2.4 Relationships of SPAD Values and NO_3^- Content with Maize Yield and Development of Diagnostic Fertilization Models

As shown in Table 2, both SPAD values and NO_3^- content at different growth stages showed significant quadratic relationships with yield. The fitting degree between NO_3^- content and yield was better than that based on SPAD values, similar to the fitting results between nitrogen diagnostic values and nitrogen application rate (Figure 2). This indicates that the nitrate reflectometer method is more accurate than the SPAD chlorophyll meter method for rapid nitrogen nutrition diagnosis and fertilization recommendation. Therefore, this study selected leaf sheath NO_3^- content as the nitrogen diagnostic indicator for fertilization recommendation.

By fitting maize yield against total nitrogen application rate, the following equation was obtained: $y = -0.0462x^2 + 39.422x + 8,665.9$ ($R^2 = 0.8835^{**}$, $n = 15$), where y represents maize yield and x represents nitrogen application rate. Solving the first derivative of the equation yielded a maximum maize yield of $17,076 \text{ kg} \cdot \text{hm}^{-2}$ at a corresponding nitrogen application rate of $426.7 \text{ kg} \cdot \text{hm}^{-2}$, which can serve as a reference for total nitrogen application to achieve maximum yield throughout the growth period. The optimal economic nitrogen application rate refers to the nitrogen rate that maximizes economic benefit per unit area, occurring when marginal output value equals marginal cost. Based on 2014 prices of $1.75 \text{ yuan} \cdot \text{kg}^{-1}$ for maize and $1.8 \text{ yuan} \cdot \text{kg}^{-1}$ for urea (pure nitrogen price of $3.9 \text{ yuan} \cdot \text{kg}^{-1}$ at 46.6% N content in urea), the optimal economic nitrogen application rate was calculated to be $402.5 \text{ kg} \cdot \text{hm}^{-2}$ when the first derivative of the equation equaled the price ratio of maize to pure nitrogen, corresponding to a maize yield of $17,049 \text{ kg} \cdot \text{hm}^{-2}$.

Substituting the optimal economic yield into the NO_3^- content-yield fitting equations in Table 2 allowed calculation of critical NO_3^- concentrations at different growth stages, which serve as important indicators for determining fertilizer adequacy or deficiency. When actual measurements fall below the critical value, nitrogen topdressing is required. By establishing linear functions between nitrogen application rate and NO_3^- content at different growth stages, a nitrogen recommendation model can be constructed for each growth stage based on measured leaf sheath NO_3^- content. In the linear relationship between nitrogen application rate and NO_3^- content shown in Figure 2, the cumulative nitrogen application before measurement at each growth stage is designated as N_{con} , the total nitrogen application for the entire growth period as N_{opt} , the nitrogen application at each growth stage as N_{d} , the actual measured NO_3^- content in production as N_{t} , and the nitrogen application at each growth stage can be calculated as:

From the linear regression relationship between NO_3^- content (N_{t}) and cumulative nitrogen application (N_{con}), we obtain: [equation would appear here]. Substituting this into the previous formula yields the NO_3^- content-based diagnostic fertilization formula. In formulas (2) and (3), a represents the intercept of the linear regression equation between NO_3^- content and nitrogen application rate, and b represents the regression coefficient. Using the economic nitrogen application rate of $402.5 \text{ kg} \cdot \text{hm}^{-2}$ as N_{opt} (total nitrogen for the growth period) and substituting a and b into formula (3), fertilization recommendation models for each growth stage were obtained (Table 3). Based on these models, the amount of fertilizer to be applied per unit change in NO_3^- content at each growth stage can be calculated—that is, the change in recommended fertilization rate caused by a one-unit change in NO_3^- content under each growth stage model. The topdressing amount at each growth stage = (critical NO_3^- content at each growth stage - measured NO_3^- content) \times nitrogen application rate per unit NO_3^- content change at each growth stage.

Discussion

Research has shown that crop nitrogen content has an extremely significant correlation with SPAD values and can effectively reflect crop nitrogen nutrition status [17]. In this study, maize leaf sheath NO_3^- concentration was closely related to soil nitrogen supply and maize nitrogen nutrition, consistent with the findings of Mi Yanhua et al. [18]. Maize leaf sheath NO_3^- content was highest at the jointing stage and most sensitive to soil nitrogen supply, decreasing with growth progression and reaching the lowest level at the grain-filling stage. This may be attributed to the high mobility of nitrogen in plants, as during this period, large amounts of nutrients are translocated from vegetative organs (leaves and sheaths) to reproductive organs (ears), with rapid nitrogen assimilation rates resulting in low free nitrate content in the plant. Wei Changzhou et al. [19] observed a similar pattern of decreasing nitrate concentration with cotton growth progression when using the reflectometer method for cotton nitrogen

nutrition diagnosis.

Geyer et al. [20] noted that maize NO_3^- content has a wide value range, and due to clear nutritional level demarcations, nitrogen abundance or deficiency at different stages can be intuitively judged by comparing numerical ranges. SPAD values directly reflect relative chlorophyll content in crops, with chlorophyll being a magnesium porphyrin compound that provides poorer feedback on minor nitrogen changes compared to ionic NO_3^- , which was confirmed in this study. For instance, leaf SPAD values showed a narrow range during the maize growth period (45.3–56.5), while NO_3^- content exhibited a much wider range (17.0–886.7 $\text{mg} \cdot \text{L}^{-1}$). The linear-plus-plateau relationship between NO_3^- content and plant total nitrogen revealed that beyond the plateau inflection point of 186 $\text{mg} \cdot \text{L}^{-1}$, continued increases in nitrogen application caused changes in NO_3^- content but did not result in corresponding changes in plant total nitrogen content. This study found that leaf sheath nitrate measurement is more effective than chlorophyll meter and total nitrogen determination in reflecting excessive nitrogen application.

Li Yinshui et al. [21] compared the suitability of SPAD chlorophyll meter, nitrate reflectometer, and spectrometer methods for rapid nitrogen nutrition diagnosis in rapeseed (*Brassica napus*), concluding that the SPAD method was the most suitable diagnostic indicator. However, the results of this study are not consistent with those findings. SPAD values depend on leaf chlorophyll absorption of specific light wavelengths, but leaf thickness varies across maize growth stages, affecting the number of chlorophyll molecules per unit area and thus influencing leaf SPAD values [22]. Additionally, the leaf base contains more veins per unit area, increasing the probability that the chlorophyll meter detection window will press on veins, resulting in lower and more variable measurements at the leaf base [13], which may explain the instability of maize leaf SPAD values observed in this experiment.

This study demonstrates that leaf sheath NO_3^- content is more sensitive than SPAD values in responding to plant nitrogen status, with minor increases in SPAD values causing exponential increases in NO_3^- content, consistent with the findings of Jia Liangliang et al. [23]. In northern China's dryland areas, nitrification is intense [24], and the primary nitrogen source available to crops is nitrate nitrogen [25]. Therefore, nitrate reflectometer testing of plant NO_3^- content can be used for nitrogen nutrition diagnosis. The nitrate testing method is feasible for nitrogen diagnosis in Xinjiang's arid regions. In practical applications, nitrate measurement techniques can be adjusted based on specific conditions to maintain concentrations within the optimal measurement range, ensuring result reliability. Based on experience from this experiment, diluting extracted crop juice 5–10 times before measurement yields reliable results in field diagnosis. The nitrate reflectometer method requires destructive sampling of leaf sheaths, petioles, or blades, making it technically more complex than the chlorophyll meter method. The SPAD chlorophyll meter method is non-destructive, simpler, and faster for information acquisition and allows repeated

measurements, but chlorophyll meter measurements show high variability, requiring at least 30 leaves to be measured and averaged, which substantially reduces representativeness [26]. In summary, both SPAD chlorophyll meter and nitrate reflectometer can be used for field crop nitrogen nutrition diagnosis, but the nitrate reflectometer method provides more accurate diagnosis of maize nitrogen nutrition status and can be used to establish fertilization recommendation models for different maize growth stages.

This paper focuses on comparing the advantages and disadvantages of SPAD chlorophyll meter and nitrate reflectometer methods for nitrogen diagnosis in drip-irrigated maize. The nitrogen recommendation model based on NO_3^- content requires further validation. The experimental results were generated from one year of data; subsequent extensive experiments should be conducted to investigate the applicability of this diagnostic model to different maize varieties in this region and to refine and optimize it.

Conclusion

Through rapid nitrogen diagnosis of drip-irrigated maize using SPAD chlorophyll meter and nitrate reflectometer, it was found that NO_3^- content at each growth stage showed better fitting degrees with nitrogen application rate and yield than SPAD values. Nitrate rapid testing is more sensitive and provides more stable data than SPAD measurement in responding to nitrogen abundance or deficiency.

Maize leaf SPAD values and leaf sheath NO_3^- content were both extremely significantly positively correlated with nitrogen application rate ($P < 0.05$). With increasing nitrogen application rate, both parameters showed different magnitudes of increase across growth stages, with the greatest increase occurring at the jointing stage, when diagnostic values were most sensitive to plant nitrogen changes. From jointing to grain-filling stage, the increase in NO_3^- content with nitrogen elevation was greater than that of SPAD values, showing more sensitive nitrogen response.

The fertilizer response equation indicated that the optimal economic nitrogen application rate for maize was $402.5 \text{ kg} \cdot \text{hm}^{-2}$, corresponding to a maize yield of $17,049 \text{ kg} \cdot \text{hm}^{-2}$. Based on nitrate reflectometer diagnosis, critical NO_3^- diagnostic values for maize at the jointing, tasseling-silking, and grain-filling stages were $729.3 \text{ mg} \cdot \text{L}^{-1}$, $536 \text{ mg} \cdot \text{L}^{-1}$, and $81.2 \text{ mg} \cdot \text{L}^{-1}$, respectively, with corresponding nitrogen application rates per unit NO_3^- change of $0.178 \text{ kg} \cdot \text{hm}^{-2}$, $0.452 \text{ kg} \cdot \text{hm}^{-2}$, and $3.82 \text{ kg} \cdot \text{hm}^{-2}$. When measured NO_3^- content falls below the critical value for a given growth stage, the required topdressing amount can be accurately calculated based on the nitrogen application rate per unit NO_3^- content change.

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Note: Figure translations are in progress. See original paper for figures.

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