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Research article

Rhizobial inoculation and UAV-derived vegetation index associated with grain yield in common bean

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Abstract: Common bean is one of the most important food legumes worldwide. However, low grain yields among smallholder farmers are often associated with insufficient mineral fertilization and difficulties in identifying nutrient deficiencies. The crop can establish symbiotic associations with nitrogen-fixing bacteria, meeting part of its nitrogen requirements through biological nitrogen fixation (BNF). We aimed to evaluate the effects of rhizobial inoculation and mineral nitrogen fertilization on the grain yield of common bean cultivars, as well as to assess the potential of the modified photochemical reflectance index (MPRI) as an indicator associated with grain yield. The experiment was conducted under field conditions in Lavras, Minas Gerais, Brazil. Seven common bean cultivars and four nitrogen sources were evaluated: inoculation with the UFLA 02-100 and CIAT 899 strains, mineral nitrogen fertilization, and a non-fertilized control. Agronomic and physiological traits were evaluated throughout the crop cycle, and aerial images were obtained at 50 days after sowing to determine MPRI. The cultivar × nitrogen source interaction was not significant for the evaluated traits. Inoculation with UFLA 02-100 resulted in grain yield comparable to mineral nitrogen fertilization despite lower shoot N accumulation, whereas CIAT 899 did not differ from the non-fertilized control in grain yield. MPRI was significantly associated with grain yield but not with shoot N accumulation, indicating its potential as a non-destructive indicator of crop performance.

Keywords: *Phaseolus vulgaris; Rhizobium*; nitrogen; genetic variability; inoculation

1. Introduction

Common bean (*Phaseolus vulgaris* L.) plays an important role in food security worldwide; however, its productivity remains highly dependent on nitrogen availability [1]. Although biological nitrogen fixation (BNF) is an inherent characteristic of legumes, common bean is generally considered less efficient in BNF than crops such as soybean [2]. Mineral nitrogen fertilization is therefore widely used to maximize grain yield despite substantial losses through volatilization, leaching, and denitrification [3]. In this context, improving nitrogen management requires tools capable of rapidly assessing crop physiological performance and canopy development under field conditions, particularly in systems where both mineral nitrogen and BNF contribute to plant nutrition.

The contribution of BNF to common bean depends on the establishment and activity of the symbiosis between the plant and rhizobia. Differences in symbiotic efficiency can affect N accumulation, leaf chlorophyll content, biomass production, and grain yield. These responses may also vary among cultivars and according to the availability of mineral N in the soil [4].

Remote sensing approaches have been increasingly adopted for the estimation of biomass, canopy vigor, and nitrogen-related traits in agricultural crops [5]. Vegetation indices derived from visible bands have shown potential for monitoring crop development and estimating grain yield [6]. Previous studies have demonstrated that SPAD (Soil Plant Analysis Development) meters and vegetation indices can be used to assess plant nitrogen status in cereals and legumes, including common bean [7,8].

Because N supply affects chlorophyll concentration and canopy development, differences in plant N status may also be reflected in vegetation indices [9]. This relationship provides a basis for testing whether image-derived indices can detect changes in crop performance associated with different N sources. Among RGB (Red-Green-Blue) -based vegetation indices, the modified photochemical reflectance index (MPRI) is calculated from the green and red bands available in conventional RGB imagery. This allows its use with UAV-acquired images without requiring near-infrared sensors, making it a simple and suitable index for field-based assessment of vegetation and canopy variability [10].

Nevertheless, the performance of vegetation indices under contrasting rhizobial inoculation and nitrogen fertilization conditions remains poorly understood in common bean. In particular, it is still unclear whether image-derived metrics can reliably reflect canopy vigor and its association with grain yield under different nitrogen sources.

We hypothesized that rhizobial inoculation would promote physiological and agronomic responses comparable to mineral nitrogen fertilization and that MPRI would be associated with differences in canopy development and grain yield variability in common bean.

Therefore, the present study aimed to evaluate the effects of rhizobial inoculation and mineral nitrogen fertilization on the grain yield of common bean cultivars and to assess the potential of the MPRI as an indicator associated with grain yield, plant growth and development traits, and accumulated shoot nitrogen under contrasting nitrogen management conditions.

2. Materials and methods

2.1. Experimental site

The field trial was carried out from February to May 2023 during the dry season (locally known as the dry season crop) in Lavras, Minas Gerais state, Brazil (21°14′ S, 44°59′ W; 918 m altitude) under rainfed conditions [4].

According to the Köppen classification, the regional climate is Cwa, characterized as subtropical

with dry winters and rainy summers [11]. During the growing season, monthly rainfall decreased from 178 mm in February to 11 mm in May, while mean air temperature gradually declined over the same period (Figure 1). The experiment was established in a clayey Oxisol previously cultivated with different crops, including inoculated soybean and common bean. Soil chemical properties were determined in the 0–20 cm layer before sowing (Table 1). The soil was acidic (pH 5.4), with low organic matter content (3.60 dag kg^{-1}) and a native rhizobial population of 5.52 × 10^3 cells g^{-1} soil. Fertilization at sowing consisted of 120 kg ha^{-1} of P_2O_5 and 350 kg ha^{-1} of K_2O supplied as single superphosphate and potassium chloride, respectively.

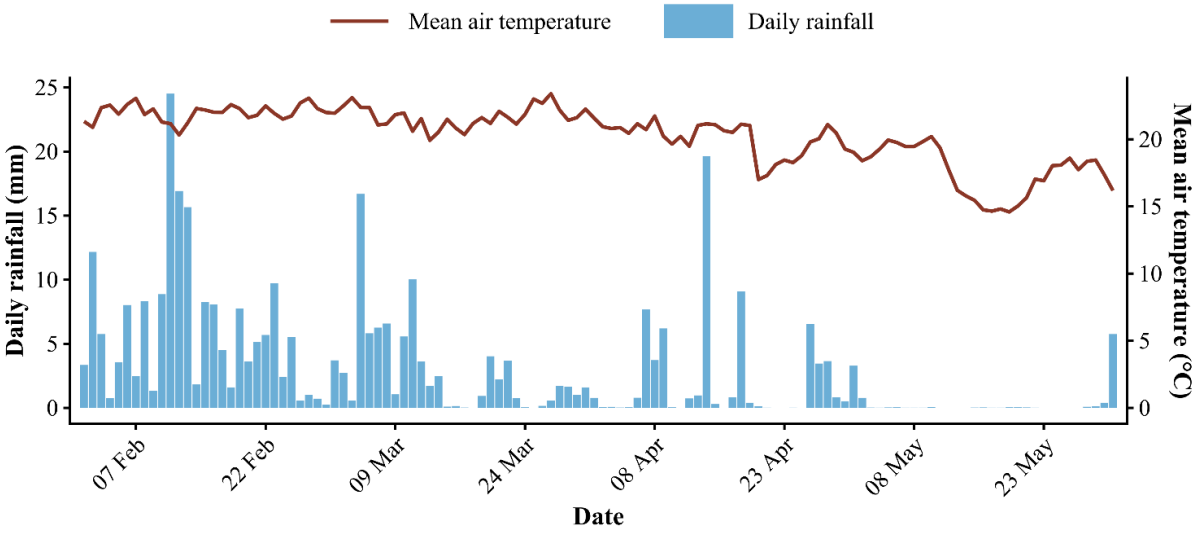


Figure 1. Daily precipitation and mean air temperature from February to May 2023 in Lavras, Minas Gerais, Brazil.

Table 1. Chemical and biological properties of soil in field environment.

pH	(P-Mehlich I)	K	Ca	Mg	Al	H+Al	SB	T
5.4	16.30	90.70	4.93	0.81	0.10	3.40	5.97	9.37
m	BS	OM	MPN					
1.65	5.97	3.60	5.52 10^3					

*Note: SB, sum of exchangeable bases; T, cation exchange capacity at pH 7; m, exchangeable aluminum saturation; BS, base saturation; and OM, organic matter; MPN, most probable number rhizobia; pH in H_2O; P and K in mg dm^{-3}; Ca, Mg, Al, H + Al, SB, and T in $cmol_c$ dm^{-3}; m and BS in %; OM in dag kg^{-1}; MPN in cells g^{-1} soil).

2.2. Experimental design and treatments

Treatments were arranged in a randomized complete block design in a 7 × 4 factorial scheme with four replications [4]. The factors consisted of seven common bean cultivars and four nitrogen supply strategies: inoculation with CIAT 899 (*Rhizobium tropici*) [12] or UFLA 02-100 (*Rhizobium etli*) [13], both obtained from the culture collection of the "Biology, Microbiology and Soil Process" laboratory at the Federal University of Lavras (UFLA), Brazil; a non-inoculated control receiving mineral

nitrogen fertilization (100 kg N ha^{-1} applied at sowing) (N+); and a non-inoculated treatment without mineral N application (N−).

Cultivars from the black and carioca commercial groups were evaluated. The black group included BRS Esteio and BRS FP403, while the carioca group comprised BRS FC 402, BRS FC 414, Pérola, BRSMG Uai, and BRSMG Zape. All cultivars presented indeterminate growth habit and normal growth cycle characteristics.

Rhizobial inoculants were prepared from the CIAT 899 and UFLA 02-100 strains using sterilized peat-based substrate mixed with liquid culture medium at a 1:2 (v/v) ratio. The strains were previously cultured in 79 liquid medium [14] at 28 °C under continuous agitation (110 rpm) for 48 h. After incubation, the bacterial suspension was incorporated into sterilized peat substrate (Pindstrup Substrate) to obtain the inoculant formulation. Final cell concentration was adjusted to approximately 10^9 viable cells g^{-1} and confirmed by plate counting. Seeds were inoculated at a rate of 100 g inoculant kg^{-1} seed.

The experiment was conducted under a no-tillage system. Sowing was performed manually without chemical seed treatment at a density of 12 seeds m^{-1}, corresponding to 200,000 seeds ha^{-1}. Experimental plots consisted of four 5-m rows spaced 0.60 m apart, considering the two central rows as the harvest area. Crop management practices followed regional recommendations for common bean cultivation [15].

2.3. Measured traits

Evaluations were performed at 25, 35, 50, and 65 days after sowing (DAS), corresponding to the V4, R5, R7, and R7/R8 phenological stages, respectively. Canopy area (CA) and SPAD index were evaluated at each of these dates using three plants per plot. The SPAD index was measured using a SPAD-502 Plus chlorophyll meter (Konica Minolta, Japan). Canopy area was estimated as the product of plant height (HT, cm), measured from the stem base to the apical meristem, and canopy width (CW, cm), measured as the distance between opposite leaf tips on different branches. Thus, CA represents an approximation of canopy dimensions based on a simplified geometric assumption rather than projected canopy area.

At flowering (R5/R6), three plants were sampled from each plot for the determination of shoot dry matter (SDM) and accumulated shoot nitrogen (AN). SDM was determined after oven-drying at 65 °C for 72 h and corresponded to the total dry mass of the three sampled plants. Nitrogen concentration was determined in the same plant material using the Kjeldahl method [16]. AN was calculated from shoot dry matter and N concentration. The value obtained for the three sampled plants was divided by three to obtain N accumulation per plant and subsequently converted to kg N ha^{-1} considering a plant population of 200,000 plants ha^{-1}.

At harvest (R9), grain yield (GY) was determined by harvesting the two central rows of each plot, adjusted to 13% moisture content, and expressed in kg ha^{-1}. Using grain yield data, nitrogen use efficiency (NUE) and relative inoculation efficiency (RIE) were calculated according to Eqs (1) and (2), respectively:

$$NUE = \left(\frac{Y_{-n}}{Y_{+n}} x \frac{\bar{Y}_{-n}}{\bar{Y}_{+n}}\right) \quad (1)$$

where:

Y_{-n} is the grain yield of a genotype under the control treatment without N fertilization,

Y_{+n} is the grain yield of the same genotype under mineral N fertilization,

$\bar{Y}_{-n}$ is the mean grain yield of all genotypes under the control treatment without N fertilization, and

$\bar{Y}_{+n}$ is the mean grain yield of all genotypes under mineral N fertilization.

$$RIE = \left(\frac{Y_i - Y_{-n}}{Y_{-n}}\right) x100 \quad (2)$$

where:
Y_i is the grain yield of a genotype under rhizobial inoculation (UFLA 02-100 or CIAT 899) and
Y_{-n} is the grain yield of the same genotype under the control treatment without N fertilization and rhizobial inoculation.

2.4. RGB image acquisition using UAV

Aerial images were acquired at 50 DAS using a Phantom 4 Pro Advanced UAV equipped with an RGB sensor operating in the blue (440–495 nm), green (495–570 nm), and red (620–750 nm) spectral bands. Seven ground control points (GCPs) were established for image georeferencing using a real-time kinematic (RTK) GPS receiver, with coordinates recorded in the UTM projection system (zone 23S, SIRGAS2000). Flight planning was performed in Pix4Dcapture (Pix4D SA, version 4.5) with 80% frontal and 70% lateral image overlap at 30 m flight altitude and 15 m s^{-1} flight speed. Flights were conducted between 10:00 a.m. and 1:00 p.m. under clear sky conditions.

Orthomosaic generation was carried out in Pix4D Mapper (Pix4D SA, version 4.5), including image alignment, GCP integration, dense point cloud generation, and orthomosaic reconstruction. Image processing and vegetation index extraction were performed in QGIS (QGIS Development Team, version 3.22.15). The orthomosaic was clipped to the experimental area, and soil masking was conducted using the LFtools plugin [17]. Plot limits were defined and a negative buffer of 0.6 m was applied to delimit the useful plot area. The MPRI was obtained from RGB imagery according to [18].

2.5. Data analysis

Assumptions of residual normality and homogeneity of variances were evaluated using Q–Q plots [19] and Bartlett's test [20], respectively. For the trait that did not follow a normal distribution, namely AN, the data were transformed using the expression $\sqrt{x+1}$. GY, AN, SPAD index, and CA were subjected to analysis of variance according to the statistical model described in Eq (3). HT, CW, and SDM were included as individual variables in the Pearson correlation analysis but were not analyzed as individual response variables in the analysis of variance.

For the temporal evaluations, analysis of variance was conducted separately for each measurement date (25, 35, 50, and 65 DAS). When significant effects were detected ($P \leq 0.05$), treatment means were compared using Tukey's honestly significant difference (HSD) test. NUE was analyzed considering cultivar and block effects, whereas RIE was analyzed considering cultivar, rhizobial strain, their interaction, and block effects.

$$Y_{ijk} = \mu + b_j + C_i + S_k + (CS)_{ik} + \varepsilon_{ijk} \quad (3)$$

where:
Y_{ijk} is the observed value of the response variable,
μ is the overall mean,
b_j is the fixed effect of block j,
C_i is the fixed effect of cultivar I,
S_k is the fixed effect of N source k,

$(CS)_{ik}$ is the fixed effect of the cultivar × N source interaction, and
ε_{ijk} is the random experimental error.

To evaluate the temporal dynamics of CA and SPAD index, regression analyses were performed using days after sowing (25, 35, 50, and 65 DAS) as a continuous variable. Regression analyses were performed using treatment means to describe general temporal trends rather than inferential repeated-measures modeling. Linear and quadratic polynomial models were fitted to describe the responses over time.

Model selection was based on the Akaike information criterion (AIC) [21], with preference given to models with lower AIC values. Linear and quadratic models were compared for each variable. For both CA and SPAD, the quadratic model showed improved fit compared to the linear model, as indicated by lower AIC values and supported by analysis of variance. Predicted curves and their 95% confidence intervals were plotted together with the observed means to illustrate temporal trends.

Experimental precision was assessed using the coefficient of variation (CV), according to [22]. Pearson's correlation coefficients were calculated to assess the relationships among GY, SDM, AN, HT, CW, CA, and the MPRI. All statistical analyses were performed in R version 4.4.0 [23]. Analysis of variance and Tukey's HSD test were performed using the ExpDes.pt package [24] and base R functions. Polynomial regression, model comparison based on AIC, and Pearson's correlation analyses were performed using functions from the stats package. Data processing and organization were performed using the dplyr [25] and tidyr [26] packages, and graphical visualizations were generated using ggplot2 [27].

3. Results

3.1. ffects of cultivars and nitrogen sources on agronomic traits

The CV ranged from 5.65% for SPAD at 50 DAS to 26.02% for GY across the evaluated variables. The cultivar × nitrogen source interaction was not significant for any of the evaluated variables. The cultivar effect was significant for all variables except canopy area at 50 DAS and NUE. Nitrogen source effects were significant for GY, AN, CA at all evaluation dates, and SPAD at 25, 50, and 65 DAS, but not for SPAD at 35 DAS (Table S1). RIE differed between rhizobial strains, with higher values for UFLA 02-100 than for CIAT 899 (Table S2).

The mineral nitrogen treatment (N+) resulted in higher AN, with values approximately twice those observed in the non-fertilized control (N−) (Figure 2A). Inoculation with the UFLA 02-100 strain reached 70% of the AN obtained under the N+ treatment, corresponding to a difference of only 11.56 kg ha^{-1}, although the treatments did differ statistically. UFLA 02-100 and CIAT 899 did not differ significantly from the N− control for this variable, with a mean AN of 29.05 kg N ha^{-1} (Figure 2A).

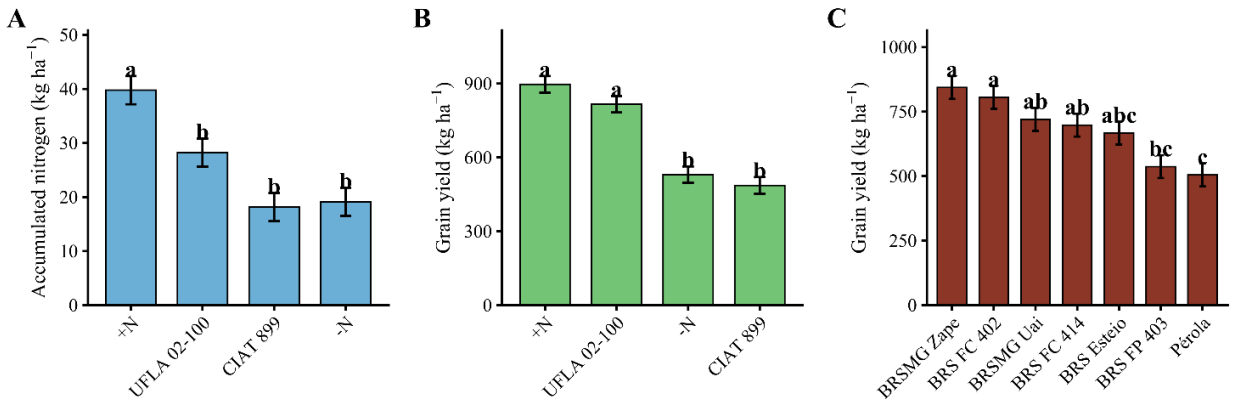


Figure 2. Accumulated nitrogen at flowering (A); grain yield under different nitrogen sources (B); and common bean cultivars (C). Means are expressed in the original scale. Error bars represent the standard error (SE) of the mean. Means followed by different letters differ significantly according to Tukey's HSD test ($P \leq 0.05$).

Inoculation with the UFLA 02-100 strain resulted in GY statistically similar to the mineral nitrogen (N+) treatment, with a mean of 856.4 kg ha^{-1}, despite lower AN accumulation compared with N+. The CIAT 899 strain and the non-fertilized control (N−) did not differ in terms of GY, showing yields that were, on average, 348 kg ha^{-1} lower than those observed for the other nitrogen sources (Figure 2B). Among the cultivars, BRSMG Zape and BRS FC 402 achieved GY values above 800 kg ha-^{1}, whereas Pérola showed lower performance, with yields around 500 kg ha-^{1} (Figure 2C). BRS FC 414 and BRS FC 402 had higher CA, particularly at 35 and 65 DAS, whereas BRS FC 414 and Pérola had higher SPAD values from 35 DAS onward. BRSMG Uai showed lower values for both traits (Table 2).

Table 2. CA and SPAD index of common bean cultivars at different DAS.

Cultivar	CA 25 DAS (cm²)	CA 35 DAS (cm²)	CA 65 DAS (cm²)	SPAD 25 DAS	SPAD 35 DAS	SPAD 50 DAS	SPAD 65 DAS
BRSMG Zape	397 bcd	987 bc	1789 abc	43.7 ab	49.7 bc	57.1 bc	49.7 ab
BRS FC 402	461 ab	1254 a	1948 a	43.6 ab	46.0 d	56.4 c	46.5 bc
BRSMG Uai	355 cd	710 d	1441 c	41.4 b	45.3 d	54.0 c	41.6 d
BRS FC 414	536 a	1171 ab	1893 ab	46.6 a	53.7 a	59.9 ab	51.3 a
BRS Esteio	371 bcd	762 cd	1468 c	42.9 ab	48.1 cd	55.9 c	44.0 cd
BRS FP 403	438 abc	829 bcd	1593 bc	45.6 a	48.5 cd	54.7 c	44.0 cd
Pérola	330 d	954 abc	1782 abc	46.6 a	52.7 ab	61.4 a	50.9 ab

*Note: Means followed by different letters differ significantly according to Tukey's HSD test ($P \leq 0.05$).

3.2. Temporal physiological responses of common bean under different nitrogen sources

CA increased from 25 to 65 DAS under all nitrogen sources (Figure 3A). Differences among nitrogen sources varied across evaluation times (Figure 3C). At 25 and 35 DAS, N+ resulted in greater CA than N−, CIAT 899, and UFLA 02-100. At 50 DAS, N+ and UFLA 02-100 had greater CA than

CIAT 899, while N− did not differ from the other treatments. At 65 DAS, greater CA was observed for UFLA 02-100 and N+ compared with N− and CIAT 899.

Overall, SPAD index showed a similar temporal pattern across nitrogen sources, increasing up to approximately 50 DAS and decreasing thereafter (Figure 3B). At 25 DAS, N− showed a higher SPAD index than N+ and CIAT 899. No differences were detected at 35 DAS (Figure 3D). At 50 DAS, UFLA 02-100 had a lower SPAD index than the other treatments, whereas at 65 DAS, UFLA 02-100 had a higher SPAD index than the other treatments.

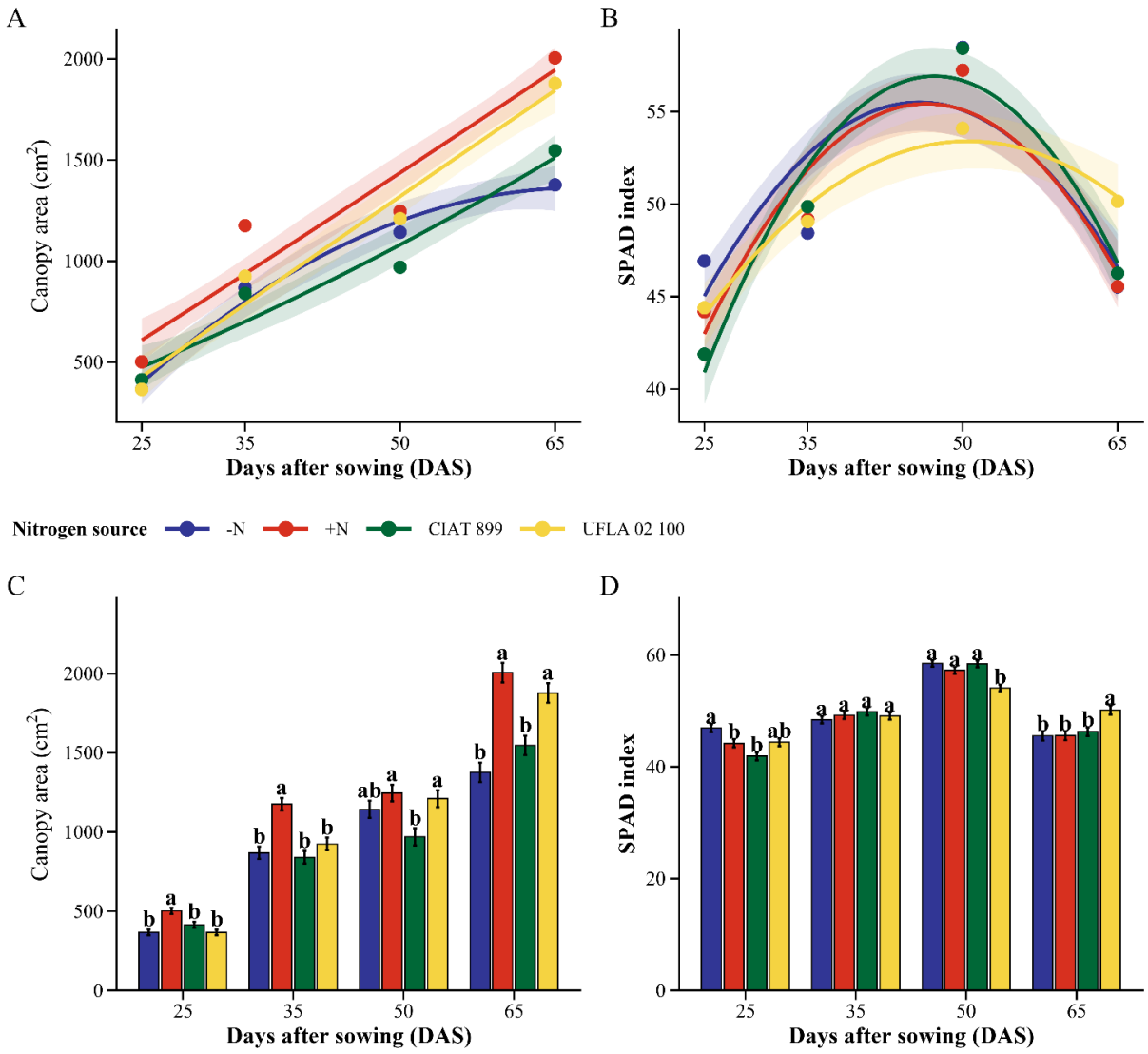


Figure 3. Canopy area and SPAD index under different nitrogen sources. (A, B) Observed means and quadratic regression fits with 95% confidence intervals. (C, D) Different letters indicate significant differences according to Tukey's HSD test ($P \leq 0.05$); ns, not significant.

3.3. Relationships among physiological, growth, and yield-related traits

SDM was positively correlated with both GY and AN (Figure 4). GY was also positively correlated with CA, AN, and the MPRI. No association was detected between AN and MPRI. HT and CW were positively and significantly correlated with each other, but neither trait was significantly

correlated with grain yield.

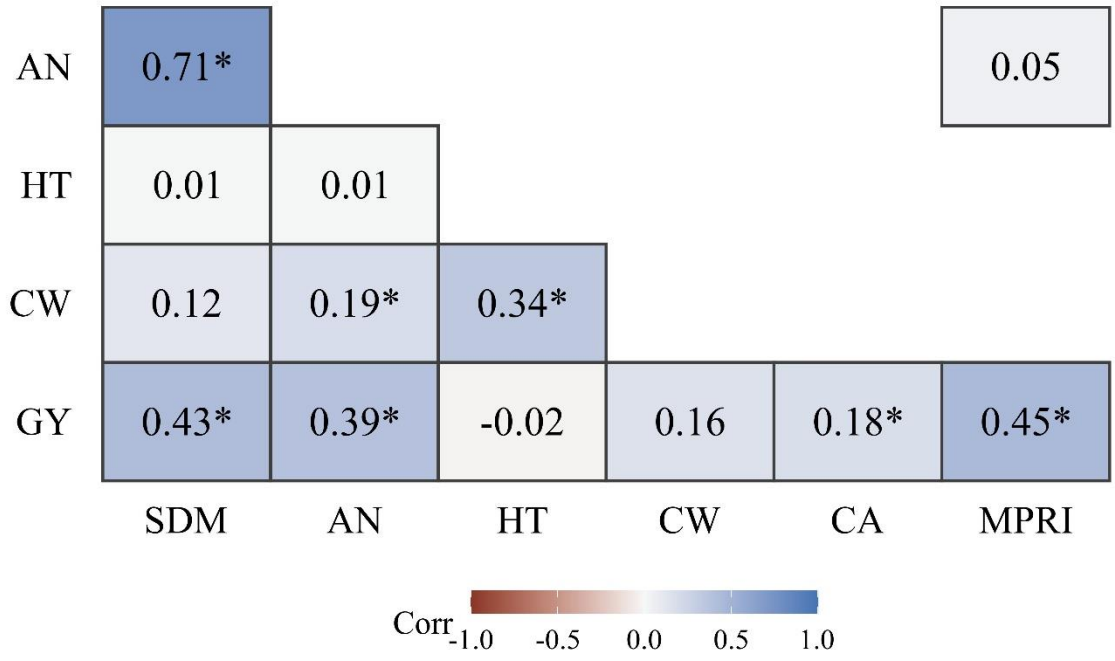


Figure 4. Correlation matrix among agronomic traits and vegetation indices in common bean: Shoot dry matter (SDM), accumulated shoot nitrogen at flowering (AN), plant height (HT), canopy width (CW), canopy area (CA), modified photochemical reflectance index (MPRI), and grain yield (GY). *Significant at $P \leq 0.05$ according to the t-test.

4. Discussion

4.1. Agronomic and temporal physiological responses of common bean cultivars to different nitrogen sources

The UFLA 02-100 strain, despite resulting in lower accumulated shoot nitrogen at flowering, promoted grain yield statistically similar to that obtained under mineral nitrogen fertilization. It is important to note that, although mineral N fertilizer was applied in the N+ treatment, root nodules were still observed in these plants. The establishment and maintenance of nodulation depend on systemic signaling mechanisms related to the nitrogen status of the plant rather than exclusively on nitrate availability in the soil. Thus, even under mineral N supply, nodulation may persist when plant physiological demand is not fully satisfied, allowing the simultaneous occurrence of mineral N uptake and BNF [28]. Therefore, the combined contribution of mineral fertilization and BNF may have contributed to the greater N accumulation observed in this treatment.

In addition, the absence of cultivar effects on NUE suggests similar nitrogen use patterns among the evaluated genotypes under the tested conditions. NUE is influenced by several factors, including root architecture, NO_3^- and NH_4^+ uptake capacity, metabolic activity, N translocation, and photosynthetic efficiency [29]. In this context, BNF may contribute to improving NUE by promoting a gradual and synchronized N supply throughout the crop cycle, favoring N assimilation and remobilization to the grains [30]. The agronomic performance of UFLA 02-100 reinforces its potential

contribution to N supply and utilization in common bean. SPAD values are associated with N content in common bean plants [31]. The UFLA 02-100 strain promoted lower SPAD peak values; however, it showed greater temporal stability even after flowering, which may represent an indirect indication of sustained leaf N status throughout the crop cycle.

During flowering, BNF activity generally reaches its maximum and subsequently declines progressively over the crop cycle [32]. The ability of common bean plants to maintain nodulation after flowering is influenced by several factors, including plant genotype, rhizobial strain, and environmental conditions [33]. In this context, the present results suggest that the UFLA 02-100 strain may favor a more gradual and continuous N supply to common bean plants, resulting in a less pronounced decline after flowering. However, this hypothesis should be confirmed through evaluations of nodulation dynamics throughout the crop cycle, including assessments of nodule number, size, activity, and viability.

The positive association among shoot dry matter, accumulated nitrogen, and grain yield suggests that biomass accumulation was closely related to N uptake and utilization efficiency. Greater biomass accumulation likely reflected improved overall vegetative growth and photosynthetic capacity rather than isolated structural traits such as plant height or canopy width. In agreement with this interpretation, plant height and canopy width were not significantly associated with grain yield, indicating that isolated structural characteristics do not necessarily reflect greater physiological efficiency [34,35].

Nitrogen is an essential component of chlorophyll and enzymes involved in photosynthesis. Therefore, greater N accumulation may have favored photosynthetic capacity and photoassimilate production, contributing to increased grain yield.

The low performance of CIAT 899 may have been associated with competition with the native rhizobial population in the soil (5.52×10^3 cells g^{-1} soil). Resident rhizobia can compete with inoculated strains for nodule occupancy, and previous studies have shown that the competitive ability of CIAT 899 varies according to the resident rhizobial population and soil conditions [36]. However, competition with native rhizobia alone does not explain the contrasting response of UFLA 02-100, since both inoculated strains were exposed to the same soil environment. Differences in competitiveness and adaptation to the soil–rhizosphere conditions may therefore have contributed to the distinct performance of the two strains [37].

Overall, grain yield in the present study was relatively low. Soil conditions likely influenced nodulation responses and crop performance. Relatively low soil pH and organic matter levels, together with pest and disease pressure and the presence of native rhizobia, may have negatively affected nodulation and crop development. Weather conditions should also be considered when interpreting these responses. Rainfall was abundant during the early stages of crop development, which may have favored the development of anthracnose caused by *Colletotrichum* spp. In addition, the history of successive common bean cultivation in the experimental area may have contributed to the persistence of pathogen inoculum between growing seasons. Anthracnose symptoms were observed during crop development, particularly during the grain-filling stage. The pronounced decline in rainfall toward the end of the experimental period occurred when the crop was already approaching maturity and was therefore unlikely to have substantially affected grain yield.

4.2. Vegetation index association with grain yield in common bean cultivars

The MPRI measured at 50 DAS showed a significant association with grain yield, indicating its potential as a non-destructive indicator of crop performance in common bean. Since the evaluations were performed during the reproductive phase, a stage strongly associated with reproductive

establishment and canopy functioning, the relationship between MPRI and grain yield likely reflects differences in canopy vigor and photosynthetic activity among treatments and cultivars [38].

However, MPRI was not significantly correlated with accumulated shoot nitrogen. Although vegetation indices based on canopy color are often associated with plant N status, this relationship may be weaker in leguminous species. Spectral responses associated with leaf greenness are generally more effective for estimating N status in non-legume crops [39].

In legumes, biological nitrogen fixation may reduce the direct relationship between canopy color and plant nitrogen accumulation, which could explain the weak association between AN and MPRI observed in the present study. Furthermore, MPRI may be more closely associated with canopy characteristics than with plant N concentration itself [40,41], indirectly contributing to its association with grain yield.

This study was conducted during a single growing season under rainfed dry-season conditions. Therefore, the performance of UFLA 02-100 and the association between MPRI and grain yield should be interpreted within these experimental conditions. In addition, nodulation dynamics and BNF were not quantified throughout the crop cycle. Further studies across growing seasons and environments are needed to assess the consistency of these responses.

5. Conclusions

The UFLA 02-100 strain promoted grain yield comparable to mineral nitrogen fertilization despite lower shoot N accumulation, supporting its potential as an alternative N source for common bean. NUE did not differ among cultivars, whereas temporal SPAD responses varied among nitrogen sources. MPRI was significantly associated with grain yield but not with shoot N accumulation, supporting its potential as a non-destructive indicator of crop performance in common bean. These findings indicate the potential of UFLA 02-100 for N management and of MPRI for crop monitoring. However, because the study was conducted during a single growing season under rainfed dry-season conditions, these findings should be validated across additional growing seasons and environments.

Use of AI tools declaration

Artificial Intelligence (AI) tools were used exclusively for language editing. No AI tools were used for data analysis, interpretation, or generation of scientific content.

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Conflict of interest

The authors declare there are no conflicts of interest.

Author contributions

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