

Assessment of common bean responses to light spectral composition and microbial inoculation using non-destructive methods

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Received: February 1st, 2026, Accepted: March 31st, 2026; Published: June 4th, 2026

Abstract. Non-destructive methods are increasingly used to evaluate plant physiological status. This study assessed the applicability of spectrometry and chlorophyll fluorescence for monitoring common bean (*Phaseolus vulgaris*) responses to light quality and microbial seed inoculation. A two-factor growth chamber experiment was conducted using LED lighting of equal intensity but different red-to-blue ratios (1:1, red-dominated, blue-dominated) and seeds that were either uninoculated or inoculated with *Rhizobium phaseoli* strains or Proseed-Met. Non-destructive measurements were performed on the same leaves using a spectroradiometer RS-3500 and a FluorPen FP110 fluorometer. Vegetation indices were calculated to evaluate stress, pigment content, senescence, and water status, while fluorescence parameters described photosynthetic performance. Spectrometric indices more clearly reflected light treatment effects, showing higher pigment content under red light, greater senescence under balanced light, and increased stress under red-dominated spectra. Fluorescence parameters were mainly affected by microbial inoculation and were higher in inoculated plants. Limited correlations between the two methods indicated that they capture different aspects of plant physiology. Blue-dominated light increased pod number, whereas red light reduced pod and seed mass. Microbial inoculation alone did not significantly affect yield, but the highest seed yield was observed in *Rhizobium*-inoculated plants under blue light. The results highlight the importance of light spectral composition for bean productivity and support the combined use of spectrometric and fluorescence methods for comprehensive physiological assessment.

Key words: chlorophyll fluorescence, LED, *Phaseolus vulgaris*, spectrometry, vegetation indices.

INTRODUCTION

Non-destructive plant research methods are increasingly applied to assess plant vitality and physiological status without causing damage, thereby enabling repeated measurements throughout the growing period. The selection of appropriate methods largely depends on the availability of instrumentation; however, plant stress detection

generally relies on two complementary, non-destructive approaches: passive reflectance-based spectral methods and chlorophyll fluorescence measurements.

Vegetation indices (VIs), such as NDVI, EVI, NDRE, and other red-edge metrics, are widely used to non-destructively monitor canopy greenness, biomass, and pigment content (Křížová & Kumhálová, 2017; Jelínek et al., 2020; Barboza et al., 2023). These indices are particularly valuable for large-scale vitality monitoring and phenological assessment. Nevertheless, VIs have well-documented limitations, including signal saturation at high leaf area index, sensitivity to soil background and atmospheric conditions, and reduced sensitivity to early physiological stress occurring prior to visible pigment degradation (Pettorelli et al., 2011).

In contrast, chlorophyll fluorescence measurements provide direct insight into the functional state of photosystem II (PSII) and photosynthetic efficiency, allowing early detection of stress responses before structural or visual changes become apparent. As such, fluorescence-based techniques offer physiological information, whereas vegetation indices primarily reflect structural and biochemical properties (Baker, 2004). It is also useful in symbiosis studies, as the presence of microorganisms (e.g. mycorrhizal fungi, nitrogen-fixing bacteria or endophytes) often affects plant photosynthetic activity, nutrient uptake and stress tolerance. Fluorescence parameters such as F_v/F_m , $\Phi PSII$ and NPQ allow us to determine whether the symbiosis improves the plant's photophysiological state (Murchie & Lawson, 2013).

Studies demonstrate that combining vegetation indices (structural and pigment-related information) with chlorophyll fluorescence significantly improves the detection, attribution, and quantification of plant stress. (Baker, 2004; Galieni et al., 2021; Zhang & Peñuelas, 2023). However, there is no consensus in the literature on the most informative fluorescence parameters that characterise changes in physiological conditions in plants under stress or influenced by symbiotic systems. As G. Garab et al. (2023) indicate, chlorophyll fluorescence is not merely a readout of the reduction of plastoquinone molecules (QA); it reflects the complex dynamics of PSII activity, which requires a fundamental interpretation of F_v/F_m and chlorophyll fluorescence kinetics. The sensitivity of different fluorescence parameters also varies. This sensitivity, depending on plant species, has also been observed when studying plant mineral nutrition (Tan et al., 1999; Pereira et al., 2000).

Garden beans (*Phaseolus vulgaris* L.) are among the most important legume crops worldwide, valued for their significant nutritional, agronomic, and socio-economic contributions. They are a major source of plant-based protein, complex carbohydrates, dietary fibre, vitamins, and essential mineral elements. Agronomically, garden beans play a key role in sustainable cropping systems through symbiotic associations with *Rhizobium* bacteria, enabling biological nitrogen fixation and reducing reliance on synthetic nitrogen fertilisers. Garden beans are highly adaptable to diverse climatic conditions and production systems, ranging from open fields to controlled environments. (Singh et al., 2023)

The spectral quality of light regulates key physiological and developmental processes in beans, including photosynthesis, leaf morphology, biomass allocation, and nutrient assimilation, through wavelength-specific absorption by photosynthetic pigments and activation of photoreceptors. Red and blue wavelengths are especially critical, as they coincide with chlorophyll absorption peaks and have been shown to enhance photosynthetic performance, chlorophyll accumulation, and vegetative growth

in bean plants, whereas imbalanced or monochromatic spectra can lead to suboptimal morphology and reduced biomass (Hogewoning et al., 2010). Blue light plays a central role in stomatal regulation and chlorophyll synthesis, while red light promotes leaf expansion and carbon fixation efficiency, making their combination particularly effective for bean cultivation under LEDs. Additionally, modifications in the red:far-red ratio influence phytochrome-mediated responses in beans, affecting stem elongation and canopy structure (Franklin & Quail, 2010). These spectral effects highlight the importance of optimized light quality for improving garden bean growth, physiological stability, and productivity, especially in greenhouse and controlled-environment systems. (Bueno & Vendrame, 2024).

The physiological condition of the plant, particularly the process of photosynthesis, also influences the development and efficiency of symbiosis. Environmental factors, including lighting quality, alter the biochemical makeup of plant root exudates, which then impacts the activity of microorganisms, including rhizobia, in the rhizosphere (Kuzakov & Domanski, 2000; Yermko et al., 2025). Although there are no direct studies on how the spectral composition of light affects garden beans (*Phaseolus vulgaris*) exudations, research on other species, such as lettuce (*Lactuca sativa*), exists. Zhou et al. (2020) demonstrated that the secretion of phenolic compounds could be reduced by adjusting the red and blue light composition of LED, suggesting that spectral quality plays a vital role in regulating root exudation patterns.

Despite the growing application of these methods, information regarding their use under artificial lighting conditions remains limited. This highlights the need for further research on the applicability and calibration of non-destructive vitality assessment techniques for beans grown in controlled-environment and artificial-light systems.

The aim of this study was to assess the effects of light spectral composition and microbial inoculation on common bean plant physiology, yield and its quality, and to evaluate the sensitivity of spectrometric data and chlorophyll fluorescence parameters as tools for detecting plant responses to these treatments.

MATERIALS AND METHODS

Plant growth and experimental design

A two-factor experiment (1st factor- light spectrum, 2nd - microbial inoculant) was conducted in the plant growth chamber of the Department of Plant Biology, Institute of Soil and Plant Sciences, Latvia University of Life Sciences and Technologies (LBTU) from September 6 till December 8, 2025.

54 common bean (*Phaseolus vulgaris*) plants were grown in 1 L vegetation pots filled with peat substratum KKS-1 (Laflora Ltd) (EC 0.3 mS cm⁻¹, PG Mix 15-10-20 1 kg m⁻³, Ca 1.4%, Mg 0.18%, pH KCl 5.1-5.9). Plants were fertilized twice during vegetation with 2% Kristalon (18-18-18) 100 mL per pot at vegetative growth and budding stages. Leaf reflectance and fluorescence analyses were done 21 day before plant harvest (end of flowering, beginning pod formation stage) as recommended by (Hassanzadeh et al., 2020). During harvesting number of well developed pods were counted, pods were dried at room temperature and then weighted, dehulled, number and weight of seeds per plant was measured, 100 seed weight was recorded. Protein content was determined with Kjeldal method at the Research Laboratory of Biotechnologies, Latvia University of Life Sciences and Technologies (LBTU).

Microbial inoculants

To assess the effect of microbial inoculation on the physiological state of beans, two microbiological preparations were used for seed treatment just before sowing. One variant was inoculated with the bacterium *Rhizobium phaseoli* (Rh) strain (10^6 cfu mL⁻¹) from the LBTU Institute of Soil and Plant Sciences collection; the other variant was inoculated with the commercially available preparation Proseed-Met (Ginias, Greece) (Pm), which contains several microbial species (10^9 cfu mL⁻¹). In the control variant, the seeds were not inoculated with microorganisms (K).

Lighting conditions during plant cultivation

Plants were grown under Multi-channel LED lamps (Heliospectra), with identical light intensity ($175 \pm 10 \mu\text{mol m}^{-2}\text{s}^{-1}$) and 16 h photoperiod across all treatments, while the proportions of blue and red light differed. (Fig. 1, A) In the treatment (W), the ratio of red (wavelength 625–700 nm) to violet/blue light (wavelength 380–499 nm) was ~1:1, while the comparative treatments were dominated either by red (R) or blue (B) light with illumination. In variant R, red light was dominant. The ratio of red to blue light was approximately 2:1, whereas in variant B the shortest wavelengths of visible light were dominant, and under this lighting the ratio between red and blue light was such that the growing bean plants received approximately twice as much blue light as red light (Fig. 1, B). The proportion of green light (500–564 nm) in the spectrum was 7–9% ($W < R < B$), yellow light (565–589 nm) accounted for 3.1–3.5%, orange light (590–624 nm), while far-red light (701–760 nm) made up 0.4–0.6%.

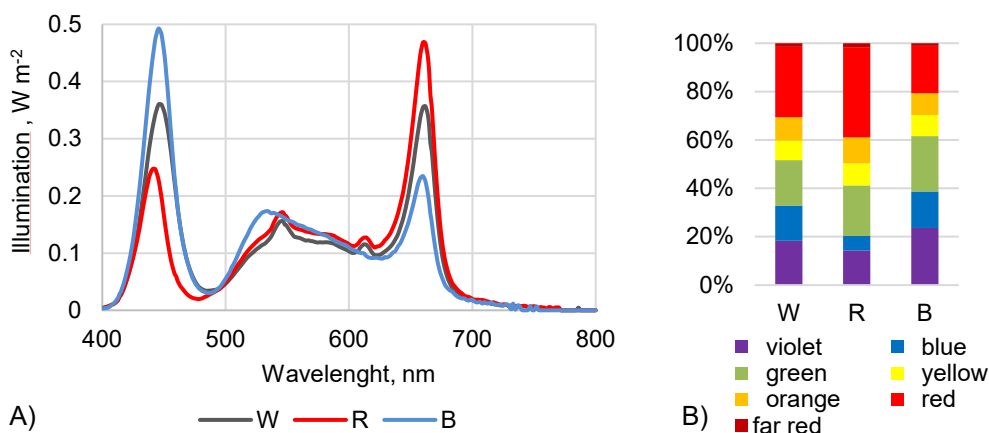


Figure 1. Spectral characterization of illumination.

A) – Spectral distribution of illumination (W m^{-2}); B) – Spectral composition (%) of LED light treatments. W – white- balanced red and blue light; R – red dominant light; B – blue dominant light.

The optical properties of the light were measured using a digital spectrometer MSC15 (Gigahertz-Optik).

Chlorophyll fluorescence

Plant photosynthetic parameters were assessed using fluorescence measurements with a chlorophyll fluorometer (FluorPen FP110, PSI, Czech Republic). The OJIP dark-

adapted method was used to assess the physiological state of plants. Fluorescence was measured on the youngest fully developed leaf and the oldest leaf of each plant. Several parameters were analysed from the resulting fluorescence transient curves, including Fo, Fj, Fi, Fm, Fv, Fj, Mo. A description of the fluorescence parameters used is provided in Table 1. The conditions for the OJIP test were consistent across all measurements. The dark-adaptation period was always 30 min, with the leaf clip in place. The fluorescence transient was induced by applying an actinic light pulse at 3,500 $\mu\text{mol photons m}^{-2} \text{s}^{-1}$.

Table 1. Description of the fluorescence parameters (Strasser et al., 2004)

Fluorescence parameters	Description
Fo	Initial fluorescence obtained in a dark-adapted sample
Fj	Fluorescence at 2 mS after illumination of a dark adapted sample
Fi	Fluorescence at 30 mS after illumination of a dark adapted sample
Fm	Maximum fluorescence after illumination of a dark adapted sample
Fv	Maximal variable fluorescence
Mo	Approximated initial slope of the fluorescence transient, expressing the rate of rcs' closure

Leaf reflectance and calculated Vegetation Indices

After fluorescence measurement the same leaves were used for detection of reflectance performed using the spectroradiometer RS-3500 (Spectral Evolution). Based on the obtained data, 56 vegetation indices were calculated to evaluate plant stress, pigment content, and water status. Table 2 gives the equations for vegetation indices that showed a significant effect of at least one of the parameters or their interaction.

Table 2. Hyperspectral vegetation indices

Vegetation index/abbreviation	Equation	Reference
Plant stress indices		
Photochemical reflectance index (PRI)	$\frac{(W531-W570)}{W531+W570}$	(Gamon et al., 1992)
Plant Senescence Reflectance Index PSRI	$\frac{W678-W500}{W750}$	(Merzlyak et al., 1999)
Pigment pool indices		
Carotenoids/ CRI	$W510^{-1} - W550^{-1}$	(Gitelson et al., 2001)
Greenness Index GI	$\frac{W554}{W677}$	(Zarco-Tejada et al., 2001)
Lichtenthaler index 1 LIC1	$\frac{W800-W680}{W800+W680}$	(Lichtenthaler, 1996)
Lichtenthaler index LIC2	$\frac{W440}{W690}$	(Lichtenthaler, 1996)
Normalized Difference Vegetation Index NDVI	$\frac{W760-W670}{W760+W670}$	(Padilla et al., 2017)
Water content indices		
Water use efficiency WBI2	$\frac{W950}{W900}$	(Peñuelas, & Filella,1998)

W λ denotes reflectance at wavelength λ (nm).

Statistical analyses were performed using JASP software. The effects of light spectrum and microorganism type, as well as their interaction, were evaluated using two-way ANOVA followed by Tukey’s HSD post hoc test at a significance level of $p < 0.05$. Pearson’s correlation coefficient was used to assess relationships between variables.

Relative values (RV) of fluorescence parameters and vegetative indices were calculated as follows (Eq. 1). The relative values (RV) used to reflect differences in yield and its parameters were calculated using the same equation, but by subtracting 1 from the result, which allows to take zero as a reference point.

$$RV = \frac{x_i}{\bar{x}} \quad (1)$$

RESULTS AND DISCUSSION

The obtained reflectance spectra enabled the identification of wavelength regions sensitive to both experimental treatments. For detecting the effects of different light spectral compositions, the most sensitive regions were 717–992 nm, 1,052–1,056 nm, and 1,064–1,130 nm. In contrast, the effects of microbial preparations were primarily detected in the spectral regions 701–711 nm, 988–1,032 nm, and 1,125–2,500 nm (Fig. 2, a & b).

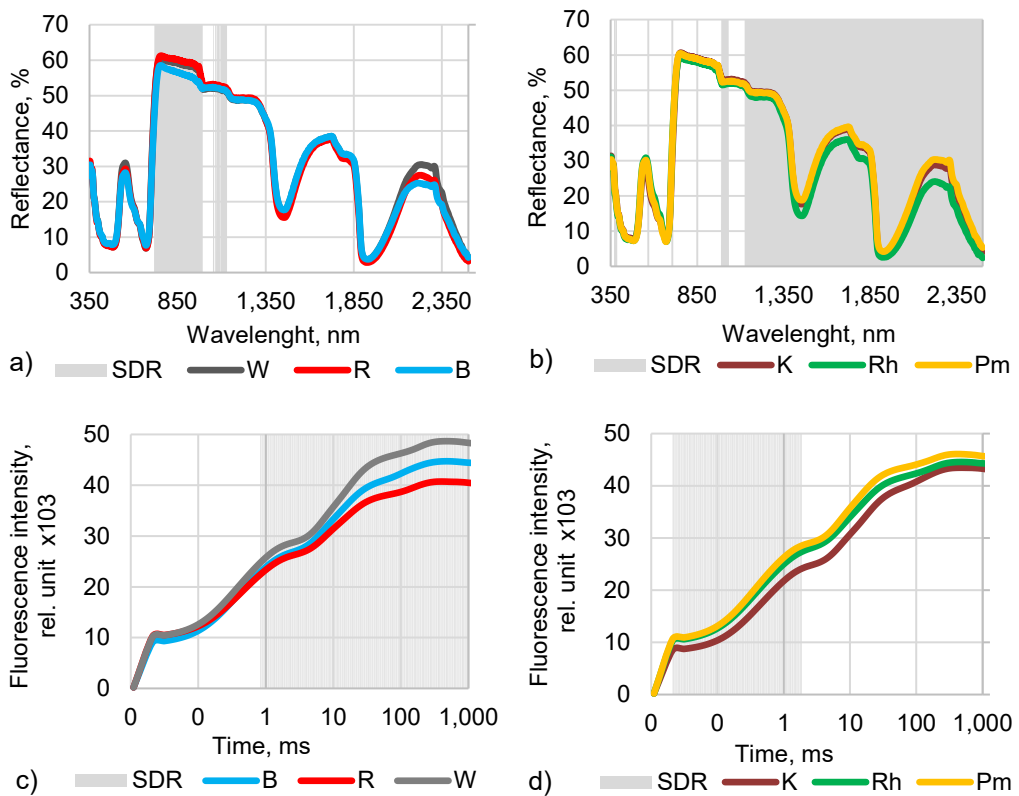


Figure 2. Reflectance spectra (a & b) and fluorescence intensity spectra (c & d) of common bean leaves.

SDR – region where significant differences between treatments in reflectance or fluorescence are detected at each wavelength or time unit respectively. W – white- balanced red and blue light; R – red dominant light; B – blue dominant light; K – without additional seed inoculation; Rh – seeds are inoculated with *Rhizobium*; Pm – seeds were inoculated with Proseed-Met.

These results indicate that light spectral composition has a stronger influence on leaf structural properties, whereas microbial preparations are more likely to affect the biochemical composition of leaves. This follows from studies by other scientists, which indicate that leaf reflectance in the near-infrared region (NIR; 750–1,350 nm) is affected primarily by leaf structure, whereas reflectance in the visible region (400–700 nm) is determined mostly by photosynthetic pigments, and reflectance in the middle-infrared region (1,350–2,500 nm) by water/ dry matter content (Slaton et al., 2001; Li et al., 2023; Li et al., 2026).

Analysis of the OJIP fluorescence induction curve reveals differences between samples at the point 0.1–1 s, corresponding to the maximum fluorescence intensity (F_m) of plants exposed to lights of varying spectral composition (Fig. 2, c). However, when comparing different inoculations, differences are evident in the early stages of the fluorescence curve (Fig. 2, d). A higher F_m value indicates more efficient energy transfer within the antenna complex and fewer energy losses. These differences align with known effects of spectral light composition on photosynthetic efficiency, as described in the literature (Janeeshma et al., 2022). White light, which covers both blue and red wavelengths, facilitates relatively balanced excitation of PSII and PSI, promoting efficient electron transport. This is usually linked to higher F_m values and a more stable F_v/F_m ratio. Under blue-spectrum illumination, F_m was lower than under white light, suggesting a partial decline in PSII efficiency and possibly an increase in NPQ, which aligns with these findings and is consistent with literature data (Wu, 2016; Zhou et al., 2020). The lower curve observed in plants exposed to predominantly red light may be due to shifts in the balance of electron transport between photosystem 1 (PSI) and photosystem 2 (PSII), as indicated by studies such as Janeeshma et al. (2022). The difference in fluorescence curves between uninoculated and inoculated beans indicates that rhizosphere microorganisms affect the physiological processes of the entire plant.

Inoculating plants with microorganisms can affect both mineral elements uptake and sensitivity to environmental stressors, thereby altering the course of photosynthesis. However, the sensitivity of chlorophyll fluorescence parameters varies. Tested parameters showed significant differences between treatments. F_i , F_m , and F_v were significantly sensitive to different light spectra (Fig. 3, a), whereas F_j , F_i , F_0 , and M_o were sensitive to the effects of microbiological preparations (Fig. 3, b).

A significant interaction with light spectra was observed for parameters F_i , F_v , and F_m (Fig. 3, a). Under white light (W), which indicates higher photosystem II efficiency, the differences were statistically significant ($P < 0.001$), demonstrating a reliable distinction between plant groups. Although F_0 and F_j were higher under white light, they decreased under blue light, suggesting reduced initial fluorescence and electron transport efficiency under this condition. M_o was slightly elevated under blue light, possibly indicating accelerated reaction centre closure, a process that occurs under stress conditions when changes in the electron transport chain happen. Inoculation with microorganisms improves photosynthetic activity compared to un-inoculated plants. Significant differences among treatments were observed in the M_o , F_o , F_i and F_j parameters (Fig. 3, b). This may be because microorganisms in the rhizosphere enhance plant stress resistance. Furthermore, De Haas et al. (2025) reported that light quality can influence root exudation, thereby affecting microbial activity. Similarly, Zhou et al.

(2020) demonstrated that adjusting the red and blue light composition of LEDs can reduce the secretion of phenolic compounds, highlighting that spectral quality plays a key role in regulating root exudation patterns and plant-microbe interactions.

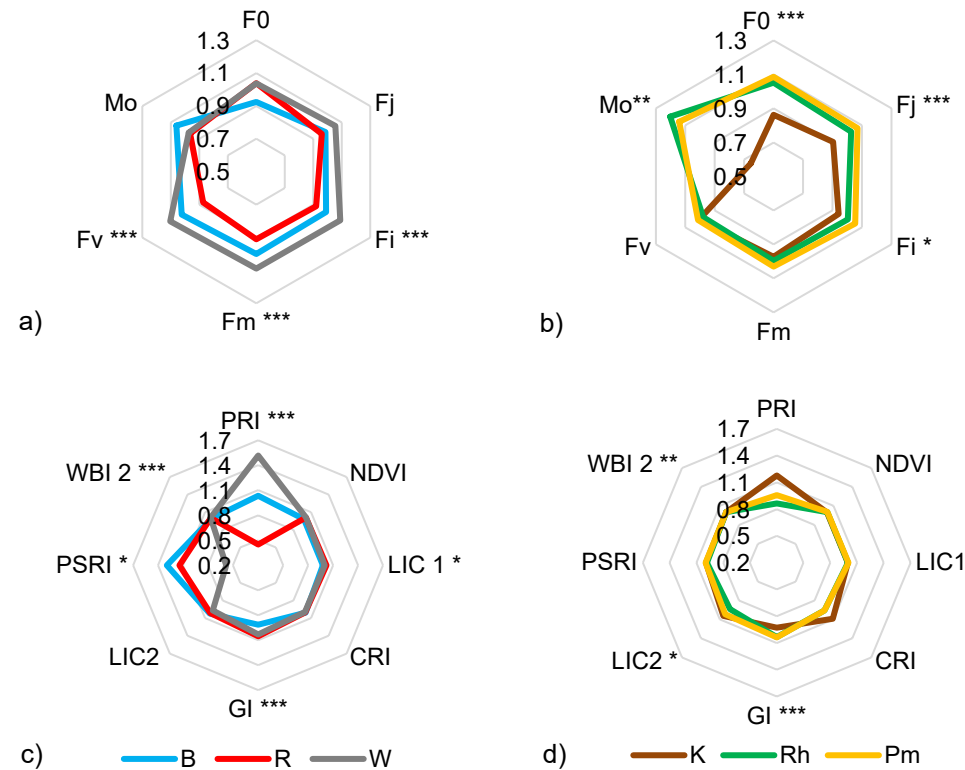


Figure 3. Relative values of fluorescence parameters and vegetative indices calculated from reflectance spectrums depending on light spectrum and seed inoculation. W – white- balanced red and blue light; R – red dominant light; B – blue dominant light; K – without additional seed inoculation; Rh – seeds are inoculated with *Rhizobium*; Pm – seeds were inoculated with Proseed-Met. Significant differences at $P < 0.5$, 0.01 , and 0.001 are reported as *, **, and ***, respectively.

Analysis of vegetation indices values and their statistical significance revealed that only 8 out of 56 indices (14.2%) showed a significant response to the studied factors. Five indices (PRI, LIC1, GI, PSRI, and WBI 2) exhibited significant dependence on the measured parameters in relation to light spectral composition, while three indices (GI, LIC2, and WBI2) were sensitive to microbial inoculation. Significant interaction effects between light and microbial treatments were observed for the indices WBI2, PSRI, GI, CRI, LIC1, NDVI, and PRI. Significant changes in pigment content were detected using the LIC1 and GI indices, following the pattern $R > W > B$. Plant senescence varied depending on the lighting treatment, with the order $W > R > B$, whereas the stress-related PRI index showed the opposite trend ($R > B > W$). (Fig. 3, c, d). Significant interaction effects between light and microbial treatments were observed for

the indices WBI2 ($P < 0.01$), PSRI ($P < 0.001$), GI ($P < 0.001$), CRI ($P < 0.05$), LIC1 ($P < 0.01$), NDVI ($P < 0.01$), and PRI ($P < 0.05$). The different sensitivity of vegetation indices has also been reported in the works of other authors. NDVI and CTR1 do not show significant differences for Batavia lettuce leaves under different illumination conditions, whereas the sensitivity of other VI are significant and $GI < PRI = CRI$. (Modarelli et al., 2022). NDVI index was non-significant also for green and purple lettuce cultivars in different light spectrums, but showed significant effect on light intensity (increased light, increased NDVI) (Hernández-Adasme et al., 2025).

Comparing the effects of inoculants on photosystem function, it was found that Fv, Fm, and Fi were higher, while F0 and Fj were lower in the *Rhizobium* variant. This indicates a positive effect of *Rhizobium* on the efficiency of photosystem II and more efficient use of energy. However, inoculation with an association of several microorganisms caused a slight stress to the plant, as the Mo value increased. *Rhizobium* inoculation improves photosynthetic efficiency, possibly positively affecting the provision of plants with mineral elements.

The experiments showed that the effects of light on bean physiological parameters were more accurately assessed by leaf reflectance. Significant changes in pigment content were detected using the LIC1 and GI indices ($R > W > B$). Plant senescence varied depending on the lighting treatment ($W > R > B$), while the stress-related PRI index followed the pattern $R > B > W$. Most of the indices demonstrated significant interactions between light treatment and microbial inoculation. In the chlorophyll fluorescence analysis, more significant differences among treatments were attributable to microbial activity (F0, Fj, Fi, and Mo). All mentioned parameters were significantly higher in treatments where seeds had been inoculated with microbiological preparations prior to sowing. To determine whether plant physiological status could be assessed using only one device, we examined correlations between vegetation indices and fluorescence parameters. Only PRI showed correlations with same fluorescence characteristics ($Tm/F0$; $Fv/F0$) $> |0.7|$. Correlation coefficients exceeding $|0.6|$ were also found between indices CRI, LIC2, and PSRI and several fluorescence parameters.

The experiments showed that the spectral composition of light has a significant effect on bean yield. Significantly more pods were obtained from plants grown under predominantly blue light. Under red light, compared with the other treatments, both pod mass and seed mass were lower. The spectral composition of light did not affect dry matter content in bean leaves, the mass of 100 bean seeds, or the protein content of the seeds (Fig. 4).

Although no significant effect of microorganisms on bean yield was demonstrated, the highest seed yield was obtained in the treatments inoculated with *Rhizobium* under blue light, whereas beans of the same treatment grown under red light produced the lowest seed yield. (Fig. 4). This may indicate an effect of the light spectral composition on the amount and qualitative composition of root exudates, which could influence symbiotic processes in the roots. There is evidence also in literature (De Lara-Del Rey & Pérez-Fernández, 2023) that lighting affects root architecture, nodule production and stress resistance.

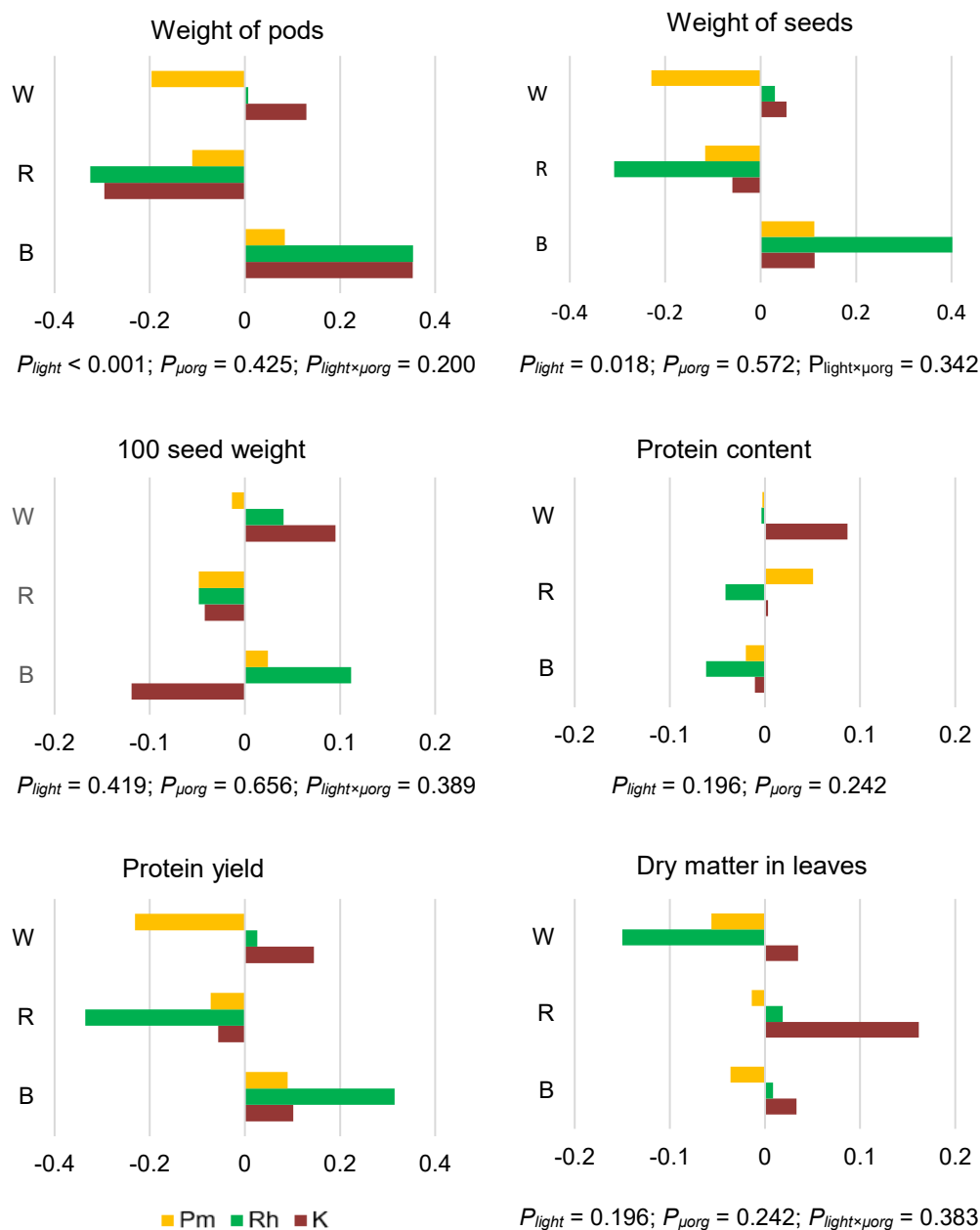


Figure 4. Relative values of common bean yield and its quality parameters.

W – white- balanced red and blue light; R – red dominant light; B – blue dominant light; K – without additional seed inoculation; Rh – seeds are inoculated with *Rhizobium*; Pm – seeds were inoculated with Proseed-Met.

A correlation was observed between fluorescence indicators and yield in treatment with rhizobia: higher Mo, Fo and Fj values were found in plants with greater pod and seed mass. The decrease in Mo observed in the non-inoculated plants could indicate mild

stress or more intense closure of reaction centres; however, it did not significantly affect yield. In turn, lower F0 and Fj values in plants inoculated with *Rhizobium* indicate more efficient energy use in photosystem II, which directly correlates with higher yield. Overall, the results highlight that microbial inoculation, particularly with *Rhizobium*, can improve both photosynthetic performance and productivity.

Unfortunately, the task in which we aimed to determine whether bean yield could be predicted using reflectance spectra and fluorescence measurements did not produce the expected results. Among the individual vegetation indices and bean pod yield, the highest correlation coefficients were found for WBI2 and LIC ($r = |0.58|$ in both cases). Correlation coefficients above 0.5 were also observed for the greenness index (GI) with pod mass ($r = |0.55|$) and seed mass ($r = |0.54|$).

In an attempt to create a combined index incorporating indices from all three groups (Table 2), the correlation was increased to $r = 0.75$ for pod yield and to $r = 0.74$ for seed mass; however, this is still considerably lower than the correlation coefficient reported by Hassanzadeh et al., (Hassanzadeh et al., 2020) who indicated a coefficient of determination for bean yield prediction in greenhouse conditions of $R^2 = 0.72$. The highest correlation with fluorescence measurements was found between bean seed yield and the parameter Fv ($r = |0.56|$). Attempts to combine both instruments in order to successfully predict bean yield did not improve the obtained results. Future work could focus on the development and validation of vegetation indices that incorporate reflected wavelengths larger than 1,000 nm, with particular attention to the sensitive spectral regions identified in this study.

CONCLUSIONS

Spectrometric measurements proved to be more effective than chlorophyll fluorescence parameters in reflecting the effects of different light spectral treatments. 14.2% of calculated vegetation indices showed statistically significant sensitivity to the studied treatments. Among the vegetation indices, PRI, LIC1, GI, PSRI, and WBI were primarily sensitive to changes in light spectral composition, whereas GI, LIC2, and WBI2 responded significantly to microbial inoculation.

Chlorophyll fluorescence parameters were more strongly influenced by microbial inoculation than by light spectral composition. Parameters Fi, Fm, and Fv were sensitive to light spectral composition, while Fj, Fi, F0, and Mo responded significantly to microbiological preparations. Significant interactions between light and microbial treatments were observed for all parameters except Fj.

Yield results confirmed that light spectral composition has a significant effect on bean productivity. Plants grown under predominantly blue light produced significantly more pods, whereas red light resulted in lower pod and seed mass compared with other treatments. Light spectral composition did not affect leaf dry matter content, the mass of 100 seeds, or seed protein concentration.

Although microbial inoculation alone did not have a statistically significant effect on total bean yield, the highest seed yield was observed in *Rhizobium*-inoculated plants grown under blue light. In contrast, the lowest seed yield occurred in the same inoculated treatment under red light. This suggests that light spectral composition may influence

the quantity and qualitative composition of root exudates, thereby affecting symbiotic processes in the root system.

Limited overlap between spectrometric and fluorescence-based assessments indicates that these methods capture different aspects of plant physiological status, but further research is needed to refine the integrated assessment.

ACKNOWLEDGEMENTS. This research was supported by project ‘Strengthening the Institutional Capacity of LBTU for Excellence in Studies and Research’, funded by The Recovery and Resilience Facility.

REFERENCES

- Baker, N.R. 2004. Applications of chlorophyll fluorescence can improve crop production strategies: An examination of future possibilities. *Journal of Experimental Botany* **55**(403), 1607–1621. <https://doi.org/10.1093/jxb/erh196>
- Barboza, T.O.C., Ardigueri, M., Souza, G.F.C., Ferraz, M.A.J., Gaudencio, J.R.F. & Santos, A.F.d. 2023. Performance of Vegetation Indices to Estimate Green Biomass Accumulation in Common Bean. *AgriEngineering* **5**(2), 840–854. <https://doi.org/10.3390/agriengineering5020052>
- Bueno, P.M.C. & Vendrame, W.A. 2024. Wavelength and Light Intensity Affect Macro- and Micronutrient Uptake, Stomata Number, and Plant Morphology of Common Bean (*Phaseolus vulgaris* L.). *Plants* **13**(3), 441. <https://doi.org/10.3390/plants13030441>
- De Haas, B.R., Oburger, E., Van Labeke, M.-C., Dhooghe, E. & Geelen, D. 2025. Light and substrate composition control root exudation rates at the initial stages of soilless lettuce cultivation. *Scientia Horticulturae* **341**, 114006. <https://doi.org/10.1016/j.scienta.2025.114006>
- De Lara-Del Rey, I.A. & Pérez-Fernández, M.A. 2023. Regulatory Effect of Light and Rhizobial Inoculation on the Root Architecture and Plant Performance of Pasture Legumes. *Agronomy* **13**(8), 2058. <https://doi.org/10.3390/agronomy13082058>
- Franklin, K.A. & Quail, P.H. 2010. Phytochrome functions in Arabidopsis development. *Journal of Experimental Botany* **61**(1), 11–24. <https://doi.org/10.1093/jxb/erp304>
- Galieni, A., D’Ascenzo, N., Stagnari, F., Pagnani, G., Xie, Q. & Pisante, M. 2021. Past and Future of Plant Stress Detection: An Overview From Remote Sensing to Positron Emission Tomography. *Frontiers in Plant Science* **11**, 609155. <https://doi.org/10.3389/fpls.2020.609155>
- Gamon, J.A., Peñuelas, J. & Field, C.B. 1992. A narrow-waveband spectral index that tracks diurnal changes in photosynthetic efficiency. *Remote Sensing of Environment* **41**(1), 35–44. [https://doi.org/10.1016/0034-4257\(92\)90059-S](https://doi.org/10.1016/0034-4257(92)90059-S)
- Garab, G., Magyar, M., Sipka, G. & Lambrev, P.H. 2023. New foundations for the physical mechanism of variable chlorophyll *a* fluorescence. Quantum efficiency versus the light-adapted state of photosystem II. *Journal of Experimental Botany* **74**(18), 5458–5471. <https://doi.org/10.1093/jxb/erad252>
- Gitelson, A., Merzlyak, M., Zur, Y., Stark, R. & Gritz, U. 2001. Non-destructive and remote sensing techniques for estimation of vegetation status. *Papers in Natural Resources*, 205–210.
- Hassanzadeh, A., Van Aardt, J., Murphy, S.P. & Pethybridge, S.J. 2020. Yield modeling of snap bean based on hyperspectral sensing: A greenhouse study. *Journal of Applied Remote Sensing* **14**(02), 1. <https://doi.org/10.1117/1.JRS.14.024519>
- Hernández-Adasme, C., Guevara, M.J., Faicán-Benenaula, M.A., Neira, R., Delgadillo, D., Muñoz, V., Salazar-Parra, C., Sun, B., Yang, X. & Escalona, V.H. 2025. Effect of Light Conditions on Growth and Antioxidant Parameters of Two Hydroponically Grown Lettuce Cultivars (Green and Purple) in a Vertical Farm System. *Horticulturae* **11**(2), 220. <https://doi.org/10.3390/horticulturae11020220>

- Hogewoning, S.W., Trouwborst, G., Maljaars, H., Poorter, H., Van Ieperen, W. & Harbinson, J. 2010. Blue light dose-responses of leaf photosynthesis, morphology, and chemical composition of *Cucumis sativus* grown under different combinations of red and blue light. *Journal of Experimental Botany* **61**(11), 3107–3117. <https://doi.org/10.1093/jxb/erq132>
- Křížová, K. & Kumhálová, J. 2017. Comparison of selected remote sensing sensors for crop yield variability estimation. *Agronomy Research* **15**(4), 1636–1645. <https://doi.org/10.15159/AR.17.016>
- Kuzyakov, Y. & Domanski, G. 2000. Carbon input by plants into the soil. Review. *J. Plant Nutr. Soil. Sci.* **163**, 421–431. [https://doi.org/10.1002/1522-2624\(200008\)163:4<421::AID-JPLN421>3.0.CO;2-R](https://doi.org/10.1002/1522-2624(200008)163:4<421::AID-JPLN421>3.0.CO;2-R)
- Janeeshma, E., Johnson, R., Amritha, M.S., Noble, L., Aswathi, K.P.R., Telesiński, A., Kalaji, H.M., Auriga, A. & Puthur, J.T. 2022. Modulations in Chlorophyll *a* Fluorescence Based on Intensity and Spectral Variations of Light. *International Journal of Molecular Sciences* **23**(10), 5599. <https://doi.org/10.3390/ijms23105599>
- Jelínek, Z., Starý, K., Kumhálová, J., Lukáš, J. & Mašek, J. 2020. Winter wheat, winter rape and poppy crop growth evaluation with the help of remote and proximal sensing measurements. *Agronomy Research* **18**(3), 2049–2059. <https://doi.org/10.15159/AR.20.176>
- Li, C., Czyż, E.A., Halitschke, R., Baldwin, I.T., Schaepman, M.E. & Schuman, M.C. 2023. Evaluating potential of leaf reflectance spectra to monitor plant genetic variation. *Plant Methods* **19**(1), 108. <https://doi.org/10.1186/s13007-023-01089-9>
- Li, Z., Ma, Z., Bao, R., Fang, W., Tang, Q., Yu, E., Song, X. & Tan, C. 2026. Exploring the hyperspectral response of leaf chlorophyll content under canopy structure and soil background variability. *European Journal of Agronomy* **175**, 127982. <https://doi.org/10.1016/j.eja.2026.127982>
- Lichtenthaler, H.K. 1996. Vegetation Stress: An Introduction to the Stress Concept in Plants. *Journal of Plant Physiology* **148**(1–2), 4–14. [https://doi.org/10.1016/S0176-1617\(96\)80287-2](https://doi.org/10.1016/S0176-1617(96)80287-2)
- Merzlyak, M.N., Gitelson, A.A., Chivkunova, O., Rakitin, B. & Yu, V. 1999. Non-destructive optical detection of pigment changes during leaf senescence and fruit ripening. *Physiologia Plantarum* **106**(1), 135–141. <https://doi.org/10.1034/j.1399-3054.1999.106119.x>
- Modarelli, G.C., Paradiso, R., Arena, C., De Pascale, S. & Van Labeke, M.-C. 2022. High Light Intensity from Blue-Red LEDs Enhance Photosynthetic Performance, Plant Growth, and Optical Properties of Red Lettuce in Controlled Environment. *Horticulturae* **8**(2), 114. <https://doi.org/10.3390/horticulturae8020114>
- Murchie, E.H. & Lawson, T. 2013. Chlorophyll fluorescence analysis: A guide to good practice and understanding some new applications. *Journal of Experimental Botany* **64**(13), 3983–3998. <https://doi.org/10.1093/jxb/ert208>
- Padilla, F.M., Peña-Fleitas, M.T., Gallardo, M. & Thompson, R.B. 2017. Determination of sufficiency values of canopy reflectance vegetation indices for maximum growth and yield of cucumber. *European Journal of Agronomy* **84**, 1–15. <https://doi.org/10.1016/j.eja.2016.12.007>
- Peñuelas, J. & Filella, I. 1998. Visible and near-infrared reflectance techniques for diagnosing plant physiological status. *Trends in Plant Science* **3**(4), 151–156. [https://doi.org/10.1016/S1360-1385\(98\)01213-8](https://doi.org/10.1016/S1360-1385(98)01213-8)
- Pereira, W.E., De Siqueira, D.L., Martínez, C.A. & Puiatti, M. 2000. Gas exchange and chlorophyll fluorescence in four citrus rootstocks under aluminium stress. *Journal of Plant Physiology* **157**(5), 513–520. [https://doi.org/10.1016/S0176-1617\(00\)80106-6](https://doi.org/10.1016/S0176-1617(00)80106-6)
- Pettorelli, N., Ryan, S., Mueller, T., Bunnefeld, N., Jedrzejewska, B., Lima, M. & Kausrud, K. 2011. The Normalized Difference Vegetation Index (NDVI): Unforeseen successes in animal ecology. *Climate Research* **46**(1), 15–27. <https://doi.org/10.3354/cr00936>
- Singh, A., Schöb, C. & Iannetta, P.P.M. 2023. Nitrogen fixation by common beans in crop mixtures is influenced by growth rate of associated species. *BMC Plant Biology* **23**(1), 253. <https://doi.org/10.1186/s12870-023-04204-z>

- Slaton, M.R., Raymond Hunt, E. & Smith, W.K. 2001. Estimating near-infrared leaf reflectance from leaf structural characteristics. *American Journal of Botany* **88**(2), 278–284. <https://doi.org/10.2307/2657019>
- Strasser, R.J., Tsimilli-Michael, M. & Srivastava, A. 2004. Analysis of the Chlorophyll a Fluorescence Transient. In G. C. Papageorgiou & Govindjee (eds.), *Chlorophyll a Fluorescence* **19**, 321–362. Springer Netherlands. https://doi.org/10.1007/978-1-4020-3218-9_12
- Tan, L.P., He, J. & Lee, S.K. 1999. Physiological responses of certain ornamental plants to sludge and artificial topsoils derived from flyash, sludge, and rengam series subsoil. *Journal of Plant Nutrition* **22**(6), 987–999. <https://doi.org/10.1080/01904169909365688>
- Wu, H. 2016. Effect of different light qualities on growth, pigment content, chlorophyll fluorescence, and antioxidant enzyme activity in the red alga *Pyropia haitanensis* (Bangiales, Rhodophyta). *BioMed Res. Int.* 7383918.
- Yeremko, L., Czopek, K., Staniak, M., Marenych, M. & Hanhur, V. 2025. Role of Environmental Factors in Legume-Rhizobium Symbiosis: A Review. *Biomolecules* **15**(1), 118. <https://doi.org/10.3390/biom15010118>
- Zarco-Tejada, P.J., Miller, J.R., Noland, T.L., Mohammed, G.H. & Sampson, P.H. 2001. Scaling-up and model inversion methods with narrowband optical indices for chlorophyll content estimation in closed forest canopies with hyperspectral data. *IEEE Transactions on Geoscience and Remote Sensing* **39**(7), 1491–1507. <https://doi.org/10.1109/36.934080>
- Zhang, Y. & Peñuelas, J. 2023. Combining Solar-Induced Chlorophyll Fluorescence and Optical Vegetation Indices to Better Understand Plant Phenological Responses to Global Change. *Journal of Remote Sensing* **3**, 0085. <https://doi.org/10.34133/remotesensing.0085>
- Zhou, C., Zhang, Y., Liu, W., Zha, L., Shao, M. & Li, B. 2020. Light Quality Affected the Growth and Root Organic Carbon and Autotoxin Secretions of Hydroponic Lettuce. *Plants* **9**(11), 1542. <https://doi.org/10.3390/plants9111542>