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POTENTIAL OF OPTICAL SENSORS FOR PREDICTING WINTER WHEAT YIELD THROUGH VARIABLE-RATE NITROGEN APPLICATION

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OPEN ACCESS

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SUMMARY

The main lever of precision agriculture is technology that provides a better understanding of the agro-ecological conditions, enables decision-making based on facts and natural laws, and facilitates precise implementation of practices based on local specificities. One of the key elements of plant production is nitrogen (N), which is traditionally applied as mineral fertilizer in large quantities. Optimizing nitrogen input is one of the priorities in precision agriculture, not only for its importance in the plant food chain but also for its environmental impact. This study investigated the potential of two optical sensors, GreenSeeker and Plant-O-Meter, in predicting nitrogen supply during the 2021-2022 growing season. The experimental material in this study included two wheat varieties, subjected to different nitrogen application rates. The objective was to estimate the potential of using NDVI (Normalized Difference Vegetation Index) measurements of wheat canopy, which are indicators of plant status, and to analyze correlations between these values and final wheat yield. GreenSeeker and Plant-O-Meter sensors, which emit light at precise wavelengths and measure plant reflectance, were used for monitoring plant status and NDVI measurements. The results showed a strong correlation between the NDVI values measured by both sensors. However, this relationship decreased during the fully ripe stage due to physiological changes in the wheat plants. The correlation between NDVI values and grain yield differed significantly between the evaluated sensors. Additional correlation analyses between NDVI measurements and yield indicated differences associated with wheat varieties, indicating that the varieties responded differently to environmental conditions. This study aligns with current agricultural approaches and contributes to more efficient and environmentally friendly agricultural practices.

Key words:
precision agriculture, optical sensors, NDVI, wheat, nitrogen

Abbreviations:
NDVI - Normalized Difference Vegetation Index; PA - Precision agriculture

INTRODUCTION

Wheat (*Triticum aestivum* L.) is one of the most important crops that significantly contribute to global food security (Shiferaw et al., 2013; Francesconi et al., 2021; Erenstein et al., 2009). In the 2020/21 growing season, the estimated global wheat planting area was 220.83 million hectares, making it one of the most extensively cultivated crops, followed by 199.11 million ha of maize and 165.22 million ha of rice (Nduku et al., 2023). Primarily used for human nutrition, it has limited use as livestock feed and in industrial processes. Wheat-based products, most notably bread, are a fundamental part of the daily diet for a large segment of the global population. Due to its agronomic adaptability, extensive cultivation, and the ease of storage and long-term grain preservation, wheat, alongside rice, serves as the most crucial source of nutrients for the majority of humanity and it is the primary source of carbohydrates in most countries (Shewry, 2009). Since the introduction of mineral fertilizers, nitrogen has become one of the most important nutrients for winter wheat. This is largely due to its significant influence on assimilate production, their distribution within the plant, the source-sink relationship of assimilates, leaf area development, and maintenance of photosynthetic efficiency. Nitrogen is an important nutrient for crop growth and development, affecting both the yield and quality of crops (Nicoletto et al., 2017; Hernández et al., 2019). Insufficient N fertilization limits crop growth, whereas excessive nitrogen application can lead to waste of resources and environmental pollution (Shahrokhnia & Sepaskhah, 2018; Ohta & Makino, 2019; Yao et al., 2020; Ljubičić et al., 2023). Reasonable application of nitrogen fertilizer can enhance nitrogen uptake by crops, increase dry matter accumulation, and ultimately increase crop yield (LV et al., 2018; Ameen et al., 2019; Guo et al., 2020; Cai et al., 2021). In cereal crops, grain is the most significant sink for assimilates (carbon and nitrogen), particularly after the flowering stage. Carbon is mainly derived from the ongoing process of photosynthesis, while most of nitrogen in the grain originates from the translocation of nitrogen previously accumulated in the plant's vegetative organs (Cartelle et al., 2006). According to Loffler et al. (1985), 60% to 92% of the nitrogen in the grain is translocated from the plant's vegetative tissues. Grain yield is more dependent on the reserves of nutrients accumulated in the vegetative parts than on newly formed assimilates from photosynthesis. Factors such as genotype, weather, and other environmental conditions before and after the flowering stage have varying impacts on nitrogen accumulation. Nitrogen concentration in plants is commonly used as a reliable indicator of nitrogen status, with different values for each plant species (Fageria, 2009). Optimizing plant nutrition is one of the key tasks of contemporary agricultural practices, particularly within the framework "precision agriculture." Numerous studies suggest that remote sensing technology holds substantial potential for providing timely and accurate information related to crop status and yield trait estimation. This information is important for decision-making in precision agriculture, as well as in large-scale breeding programs (Duan et al., 2017; Ljubičić et al., 2018; Weiss et al., 2020). The goal of crop production is to deliver precisely the resources needed to achieve maximum output. Precision agriculture (PA) seeks to enhance the effects of agronomic operations by increasing productivity and efficiency, achieving better financial outcomes and minimizing adverse environmental impacts. PA is a promising method aimed to increase the quantity and quality of agricultural output while using less input (water, energy, fertilizers, pesticides, etc.). The main objective is to lower costs, reduce environmental impact and increase both the quantity and quality of food production (European Parliamentary Research Service, 2016). As the amount of data in agriculture increases, there is a growing need to introduce some form of automated data manipulation to extract useful information usable in the decision-making system. New algorithms have been developed to convert data into useful information, optimize production processes, and reduce production risks (Kostić, 2021). According to Wang (2017), sensors are increasingly employed in agriculture to measure reflected energy in order to assess crop status (nitrogen, chlorophyll levels, development, growth stage, nutrients, canopy temperature, water content, and the presence of diseases weeds or pests) and soil conditions (soil moisture and soil temperature). Sensors, which enable easy collection of spatial and temporal data, are integral to precision agricultural production. Optical sensors, in particular, are increasingly used in modern technology, with primary applications found in automated control systems, robotics, aviation, military technology, medicine, specific applications in electrical engineering, thermomechanics, forestry, and, increasingly, in agriculture (Yule & Pullanagari, 2012; Lepore & Delfino, 2022; Pandžić et al., 2022; Simović et al., 2022). Optical sensing has become indispensable in modern agricultural practices, allowing farmers to collect information about crops, nutrition, soil conditions, and pests. These data support informed decision-making about irrigation, fertilization, application of pesticides, and other agricultural practices. In addition, optical sensors are used to assess agricultural yields prior to harvest, allowing more effective decision-making (Talal et al., 2024).

This led to the identification of vegetation indices as numerical indicators of plant status, health, and leaf development. The Normalized Difference Vegetation Index (NDVI) is a commonly used vegetation index for assessing vegetation growth status. It is significantly correlated with vegetation density and serves as an important parameter for studying vegetation coverage. Like all indices created to simplify complex datasets, the NDVI is appealing due to its capacity to quickly delineate vegetation and detect vegetative stress, making it highly valuable in commercial agriculture and land-use studies (Zhao et al., 2024; Huang et al., 2021).

This study focused on a micro-trial involving two varieties of wheat cultivated under four levels of nitrogen fertilization, while monitoring the vegetative status of the treatments through cyclic recordings using two optical sensors. The main emphasis of the study was on the application of precision agriculture principles, which rely on a comprehensive collection of geographically specific data. The research aimed to explore the effects of the treatments and wheat varieties on the final yield. Additionally, it assessed the correlation between the NDVI index, used as a measure of the vegetative status of plants, and grain yield, examining variations depending on wheat varieties. Furthermore, the study sought to determine how this correlation changes during different stages of plant development. A particular focus was placed on comparing the efficiency of the two optical sensors used in estimating the final yield. Researchers aimed to identify the sensor that provides more precise and reliable information on yield, considering different treatments and variations in wheat varieties. Therefore, the ultimate aim of the analyses was to improve agricultural production practices through application of precision agriculture principles and optimization of resource utilization.

MATERIAL AND METHODS

The study was carried out during the 2021/2022 growing season in Ravno Selo (45.446737°N, 19.670915°E), located in the northwest region of the Republic of Serbia, on carbonate chernozem soil. Chernozem is characterized by favorable mechanical composition, stable granular structure, and good physical properties. Porosity is approximately 50%, with the ratio of capillary to non-capillary pores being 3/2. Chernozem exhibits a good field water capacity (35-40%), with a significant proportion accessible to plants. Its favorable structure promotes good water permeability. The soil's neutral pH, the presence of $CaCO_3$, clay content, high structural stability of soil aggregates, moderate to high organic matter concentration, and an ideal air-water regime make chernozem highly valuable for intensive agricultural production. Topographically, the plot is entirely flat, without longitudinal or transverse slopes. The dimensions of the plot are 25 m x 400 m, covering an area of 1 hectare. The plot is used for traditional arable production with a rotation system of soybeans, wheat, and corn, and primary tillage conducted through deep plowing and plastic mulch turning. This region receives an average annual precipitation of 611 mm, with an average of 341 mm during the growing season. According to Kovačević et al. (2013), Serbia's climate typically features higher precipitation in autumn and winter and significantly less in spring, which is a critical period for wheat development. Soil chemical properties were determined from samples collected using a soil probe. Prior to primary tillage, a uniform amount of starter NP fertilizer (0-20-10 + 2 MgO+SO_3 formulation) was applied across the plot. Primary tillage was performed using a DEUTZ-FAHR 5115.4 tractor and a Lemken Europal 5 plow at a depth of 25 cm. Following primary tillage, soil preparation was carried out with a DEUTZ-FAHR 5115.4 tractor and a Vogel Noot Vibrocult S seedbed cultivator. Foreign varieties Avenue (Limagrain - LG) and Ingenio (Syngenta) were subsequently sown using a McCormick C110 Max tractor and a Sola ED-1003 seeder. In accordance with standard practice, seeding was performed in rows, with two passes of the seeder covering a width of 3 m allocated for each variety. The wheat varieties were sown with a spatial isolation of 25 cm. Plots were marked after sowing, forming plots measuring 3x10 m, on which nitrogen fertilizer was applied uniformly at rates of 0, 50, 100, and 150 kg/ha. Fertilizer was applied with a grain seeder to ensure even surface distribution. Wooden sticks and ropes were used for marking. Fertilization followed a pre-established protocol using UREA fertilizer (46%) (Tab. 1).

Table 1. Experimental design with two winter wheat varieties

Plot	**Wheat varieties used in the study**	
	Ingenio (Syngenta)	Avenue (LG)
	Rate of Application (N kg ha^{-1})	
1	150	150
2	100	100
3	50	50
4	0	0
5	150	150
6	100	100
7	0	0
8	50	50
9	100	100
10	50	50
11	0	0
12	150	150

The experiment was established using a split-plot experimental design with three replications. Measurements were conducted in multiple repetitions using both sensors during the vegetative stages of wheat development (tillering, shooting, heading, flowering, grain filling, and full ripeness) (Tab. 2). Through the vegetation stages, two optical handheld sensors were used in the experiment: the GreenSeeker and Plant-O-Meter, multispectral proximal sensor developed by the BioSense Institute in the Republic of Serbia. The main advantage of proximal, active canopy sensors is that they have their own energy source, which addresses the limitations of passive sensing devices and reduces the influence of ambient light conditions on reflectance readings (Tubaña et al., 2011; Naser et al., 2020).

Table 2. Dates of sowing, fertilizer application, NDVI measurements and harvest during the wheat experimental trial

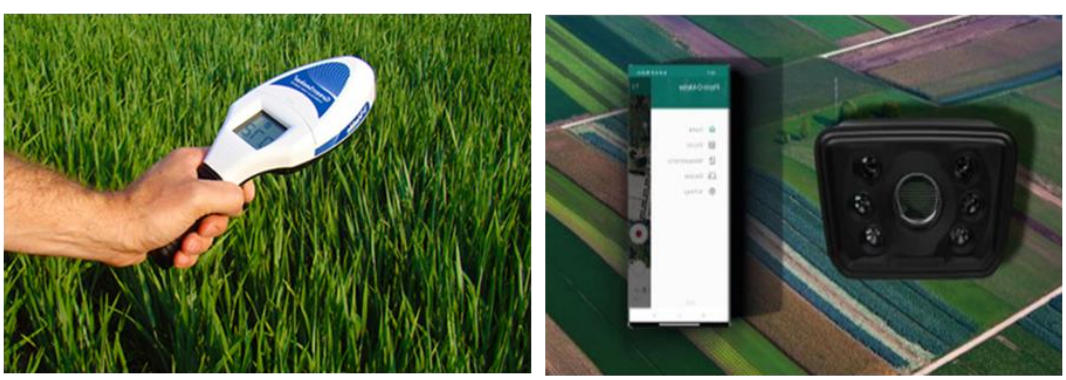
Activities conducted during the experiment	Date	Vegetation phases
Wheat sowing	20.10.2021.	ST
Application of nitrogen fertilizer	01.11.2021.	ST
Measurement I GreenSeeker	13.02.2022.	T0
Measurement II GreenSeeker + Plant-O-Meter	06.03.2022.	T0
Measurement III GreenSeeker + Plant-O-Meter	20.03.2022.	T1
Measurement IV GreenSeeker	27.03.2022.	T1
Measurement V GreenSeeker + Plant-O-Meter	17.04.2022.	T2
Measurement VI GreenSeeker + Plant-O-Meter	15.05.2022.	T3
Measurement VII GreenSeeker + Plant-O-Meter	05.06.2022.	T3
Harvest	25.06.2022.	T3

Legend: ST - Wheat germination and emergence; T0 - Early tillering phase and tillering; T1 - Start of stem elongation - Growth of the main stem between nodes; T2 - Flowering and heading; T3 - Wheat ripening

During the physiological maturity stage of wheat, samples were collected from each plot to assess grain yield. The wheat was harvested at full technological maturity. Entire stalks were manually harvested from each plot. The total sample weight was recorded, and grain weight was subsequently measured to calculate yield per unit area. The collected grain weight for each sample was recorded and moisture content was determined. All samples were adjusted to an equilibrium moisture content of 13%.

Technical description of the sensor

GreenSeeker (Fig. 1a) is one of the most commonly used handheld sensors for measuring NDVI, valued for its insensitivity to light conditions and time of day. The reflectance from the plant canopy in the visible and near-infrared regions is highly influenced by the structural and biochemical properties of the plant. These reflectance values vary depending on the plant's phenological growth phase and environmental conditions (Kumar et al., 2001). The GreenSeeker device emits multiple consecutive pulses of two spectral bands NIR and RED, where NIR and RED are the reflectance measured in the near-infrared region (770 nm) and the red region (660 nm), respectively (Tremblay et al., 2009). The intensity of the reflected light serves as a direct indicator of the plant's condition. The device displays the measured values of the NDVI (Normalized Difference Vegetation Index). The NDVI value can range from 0.00 to 0.99 depending on the growth stage, where a higher value indicates better plant condition. As a manually-operated tool, Trimble's GreenSeeker (Trimble, 2024) is user-friendly and designed to assess crop nitrogen status in order to make optimized fertilization decisions in the field. These measurements enable faster and better decision-making regarding nitrogen application, positively impacting both the crops and the environment. In combination with agronomist recommendations, the obtained NDVI values can be used to determine the dose of active nitrogen fertilizer substance. Additionally, the sensor can be complemented with a compatible mobile application from the same manufacturer, facilitating easier monitoring via mobile phones or tablets (source: https://ptxtrimble.com/).



a b

Figure 1. Utilized sensors in the field trial: a – GreenSeeker; b - Plant-O-Meter sensor

The Plant-O-Meter (Fig. 1b) is an optical IoT (Internet of things) device with decision-support functionality, designed for use as a handheld device or integrated with machinery (BioSense, 2023). This sensor is compatible with any Android-operated device through a user-friendly application, allowing users to record georeferenced point measurements and map the canopy properties of a field crop using the device's internal GPS. Sequential illumination and detection provide rapid reflectance measurements, which are wirelessly transmitted to Android-operated devices for processing and data storage (Kitić et al., 2019). The device records data in six distinct spectral bands: blue (455 nm), green (528 nm), red (657 nm), red edge (740 nm), near-infrared 1 (810 nm) and near-infrared 2 (940 nm). The Plant-O-Meter sensor provides more than 30 vegetative indices, enabling early detection of plant stress factors such as drought, heat, malnutrition, and pest-related stress. Designed for precise plant stress measurement, this portable handheld device is based on a specially designed multispectral source that integrates six light sources of the most indicative wavelengths into a single optical module, allowing for simultaneous illumination of the entire plant. These specific wavelengths have been carefully selected to cover the most indicative spectral bands and enable the calculation of multiple vegetation indices. With active illumination capabilities, the device can operate in complete darkness but also withstand extreme light conditions due to its ambient light-blocking feature. Optimal operation is achieved within a measurement range of 30-70 cm, with a recommended measurement range of 40-60 cm. The Plant-O-Meter detects changes before they become visible, analyzes and assesses the plant's health, determines its photosynthetic capacity, and indicates the need for fertilization and irrigation. Using carefully selected spectral bands, the device emits light that is reflected by the plant, providing a precise assessment of the plant's condition within seconds. The Plant-O-Meter app receives data from the device and uses the smartphone's internal antenna, supporting GPS, GLONASS, or Beidou systems for georeferencing recorded measurements. The accuracy of GPS coordinates is determined by the smartphone used during the measurement and the quality of the reception of correction signals from GPS satellites. The position can vary by 10 to 15 meters in cases of poor reception. If a more precise GPS location is required, the app also allows connection to an external GPS antenna via Bluetooth. Plant-O-Meter is accompanied by a telescopic stand with extension capabilities. For accurate measurement results, the device should be positioned directly above the analyzed plant, at a distance between 30 and 70 cm. The viewing angle should be normal to the plant, while a deviation of ±20° from the optimal viewing angle is acceptable and does not significantly affect the measurement results (source: https://biosens.rs).

This study employed descriptive statistics to summarize the data and applied regression analysis to examine the relationships between variables. Pearson's coefficient (R) was used to determine the linearity between the observed parameters. All statistical analyses were carried out using STATISTICA 13 software package (Dell Software, TX, USA). In Statistica, a straightforward best-fit regression approach was employed to model wheat traits based on NDVI data from each sensor for every measurement point throughout the trial.

RESULTS AND DISCUSSION

Figure 2 displays the results of the correlation analysis between NDVI values obtained from the GreenSeeker sensor and the Plant-O-Meter sensor throughout the experiment. Figure 2a illustrates the correlations between NDVI values from the two sensors.

The values were compared based on the criterion of the identical fields or treatments. This means that each value measured by one sensor on a particular field (treatment) was compared to the NDVI values obtained using the other sensor. Based on the coefficient of determination indicators, a strong correlation was observed among the NDVI values collected over the entire duration of the experiment. The obtained coefficient of determination of 0.80 indicates an 80% correlation between these two values, with a lack of correlation for the remaining 20% of the variation. Analysis of different recording dates revealed an extremely strong relationship in the first measurement on March 6, with a coefficient of determination of 0.87. In the subsequent measurement on March 20, the coefficient of determination reached 0.93, marking the highest level of correlation between NDVI values from the observed devices. On April 17, the data showed a modest decline to 0.90, while a more substantial divergence was observed in the measurement taken on May 15, resulting in a lower coefficient of determination of 0.49. The final measurement taken on June 5 revealed no significant correlations between NDVI values and grain yield. This lack of association between NDVI and grain yield during the grain filling period is caused by the rapid progress of grain filling stages, since the average temperatures during grain filling in early June were above average. These results align with previous research reported by Naser et al. (2020). Ljubičić et al. (2018) found no significant association between yield and NDVI during full maturity, which is expected given that the canopy dries out and NDVI declines to its lowest levels. In contrast, Gracia-Romero et al. (2019) reported stronger correlations between wheat grain yield and NDVI at the end of the season and during grain filling stages. Additionally, differences in NDVI values obtained from different devices indicated variations in the wavelengths collected by different sensors. Differences in NDVI measurements using different active and passive sensors were also observed by Ljubičić et al. (2018).

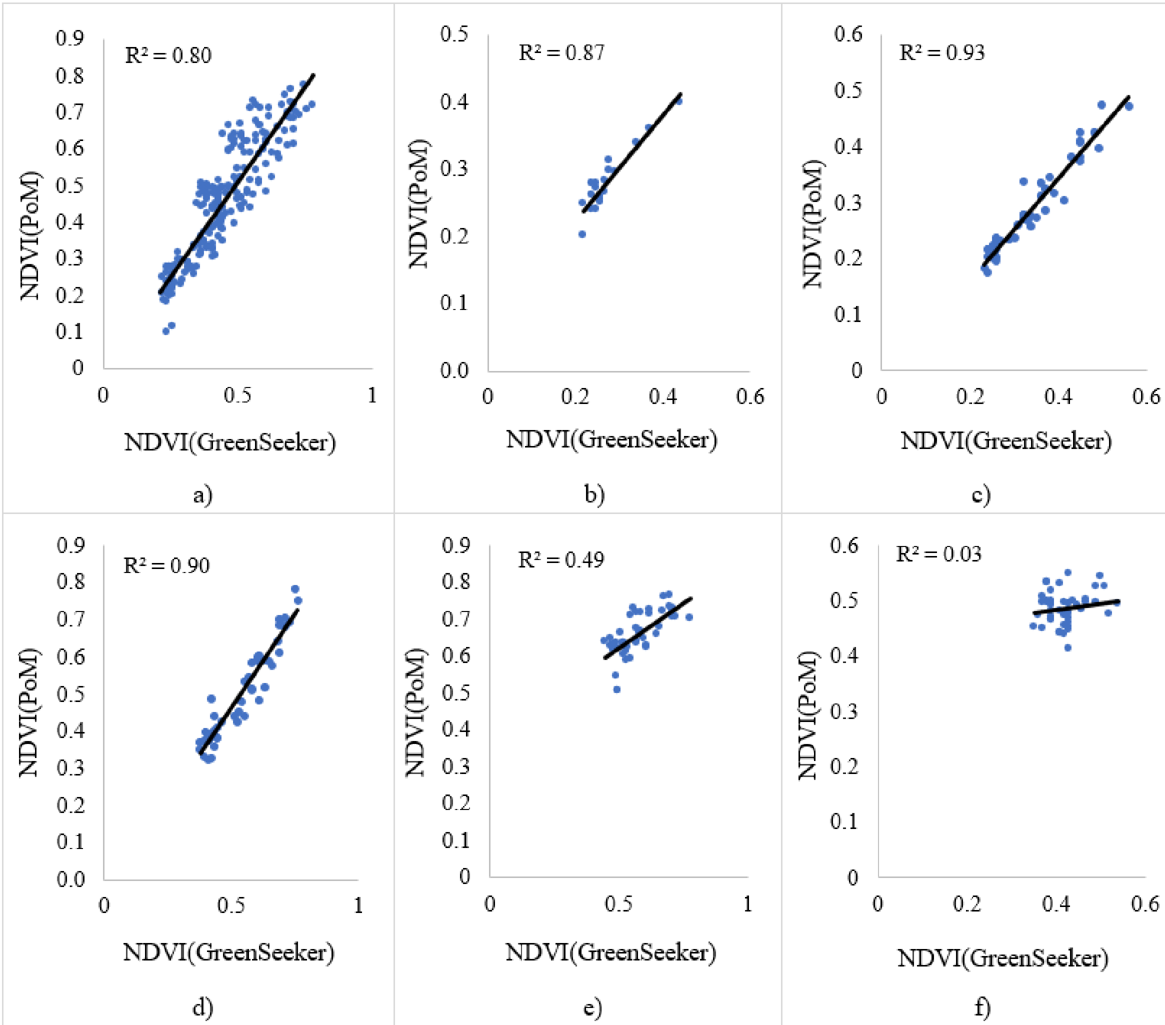


Figure 2. Correlation of NDVI values between GreenSeeker and Plant-O-Meter: a - values measured for the entire duration of the experiment; b - date 06.03.2022; c - date 20.03.2022; d - date 17.04.2022; e - date 15.05.2022; f - date 05.06.2022

An upward trend in the correlation of yield for both varieties and NDVI values measured with the GreenSeeker sensor was observed across measurement dates from February 19 to April 17, corresponding to the growth stages from late tillering to the end of heading. This period exhibited the highest variability, consistent with prior research. However, the correlation decreased in later stages as plants' vegetative mass increased (Fig. 3). The highest correlation was recorded on April 17, with an average value of 0.52.

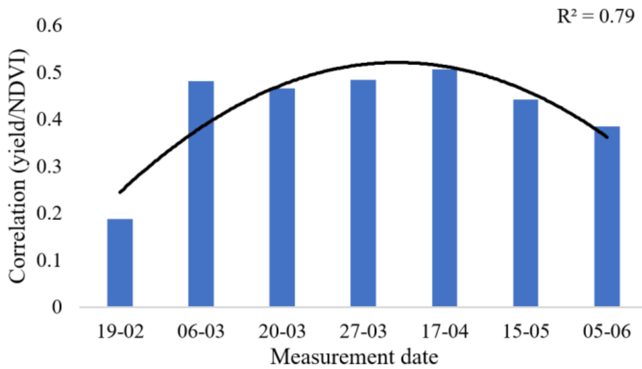


Figure 3. Correlation coefficients between grain yield and NDVI obtained by GreenSeeker sensor for both varieties

Correlation analyses between NDVI values obtained from the Plant-O-Meter sensor and the final grain yield showed marked fluctuations in the results. An initial high correlation coefficient of 0.52 was observed on March 6, followed by a sharp decline to 0.35 in the subsequent measurement. On April 17, there was a sudden increase in the correlation coefficient, while in each subsequent measurement the values were less aligned with the yield data. A negative correlation was obtained on June 5, which was atypical, although the overall trend line has a good mathematical description of 0.79% (Fig. 4). The obtained negative correlation is expected, as decreasing green biomass in the late season is usually reflected in NDVI values (Naser et al., 2020; Babar et al., 2006; Prasad et al., 2007).

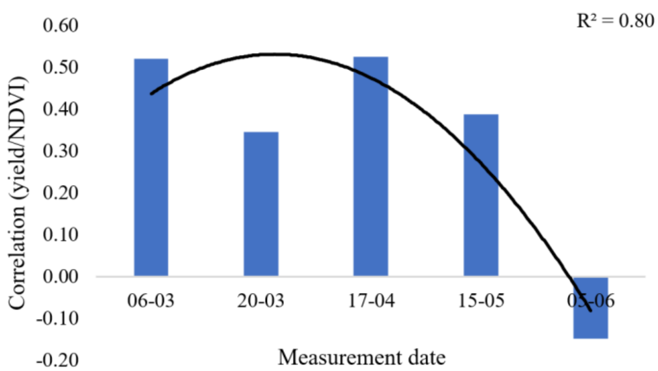


Figure 4. Correlation coefficients between grain yield and NDVI from the Plant-O-Meter sensor for both varieties

However, analyzing the correlation for each variety separately reveals some notable differences (Fig. 5). Specifically, for the Ingenio variety, the maximum correlation value (0.76) was recorded on April 17.

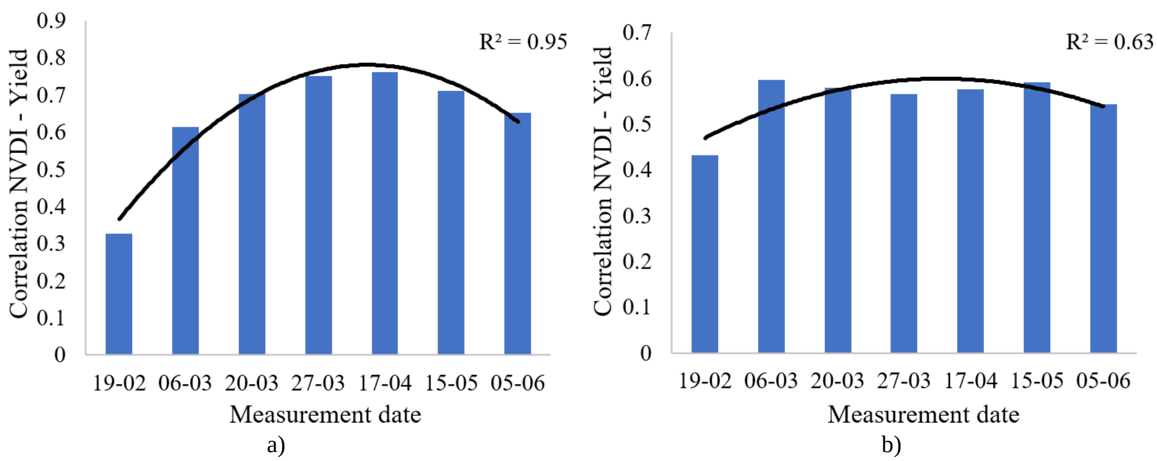
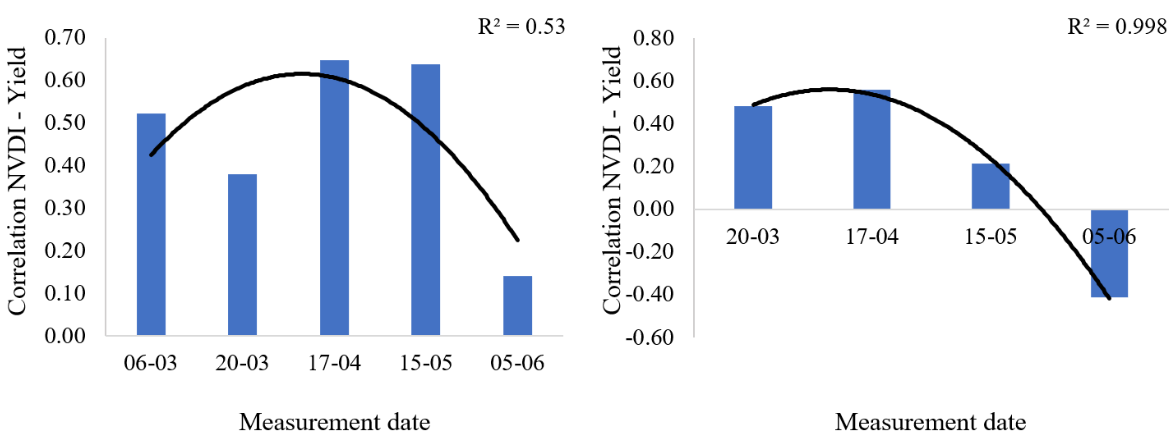


Figure 5. The correlation between grain yield and NDVI obtained by GreenSeeker for the Ingenio (a) and Avenue (b) varieties during the growing season

By the end of tillering (around the six-leaf growth stage), wheat plants have absorbed approximately one third of the nitrogen used over the entire cycle (Wiethölter, 2011). Berger et al. (2020) point out the importance of monitoring crop N content in early vegetative growth stages for planning fertilization measures, while N assessment during mature growth stages provides a valuable indication of expected yield quality. Welsh et al. (2003) found that the most effective strategies for variable rate N application in barley and winter wheat involved application of higher N doses in areas with low culm density and reduced N fertilization doses in areas with high culm density. It is also evident that the change in correlation over time follows the mathematical course of an exponential curve which, based on the coefficient of determination R^2, has a value of 0.95. In contrast, the Avenue variety displayed a different pattern of correlation with NDVI values from the GreenSeeker sensor. The highest correlation (0.6) was measured on March 6 and remained relatively stable until May 15. This early-stage correlation of NDVI with the Avenue variety is desirable for timely assessment of the plant's nitrogen requirements and possibility for variable applications. However, compared to the variety Ingenio, Avenue's value was lower, suggesting that Ingenio variety is more suitable for optical sensors like GreenSeeker. With a reliability of 0.60%, we can conclude that the variety Avenue can be assessed by the GreenSeeker sensor with less reliability. Its constant value is 0.60% within the range of dates from March 6 to May 15. For Ingenio, there was a significant increase on March 6 to nearly 0.76%, indicating higher reliability by 15-20% and, based on the GreenSeeker sensor, more accurate yield prediction. Absolute correlations for Ingenio variety exceed the value of 0.60 on April 17 and May 15, with no negative correlations observed. However, the lowest correlations were recorded on June 5. These findings are in line with previous research by Zhao et al. (2024), who demonstrated a strong correlation between NDVI and shoot biomass and nitrogen accumulation in shoots at the six-leaf growth stage, which enables estimation of these variables by NDVI.



a) b)

Figure 6. Correlation between grain yield and NDVI obtained by Plant-O-Meter for the Ingenio (a) and Avenue (b) varieties during the growing season.

For the Avenue variety, the strongest correlation between NDVI and final grain yield (0.58) was obtained by the Plant-O-Meter sensor on April 17, with the notable exception of a negative correlation on the final measurement date of June 5 (Fig. 6). Significant correlations between NDVI and grain yield from heading to grain filling in wheat have been previously documented by several researchers (Reynolds et al., 2001; Goodwin et al., 2018; Marti et al. 2007). A negative correlation in the final measurement is expected, as increased green biomass was noticed in early spring and mid-season, while decreasing green biomass was observed in the late season, which was reflected in NDVI values. These results are in accordance with findings from several other studies (Babar et al., 2006; Reynolds et al., 2012; Ljubičić et al., 2018, Naser et al., 2020). In contrast to these findings, some studies reported a positive correlation between NDVI and grain yield in late season, specifically at stages such as anthesis and mid-grain filling (Pavuluri et al., 2015; Goodwin et al., 2018).

CONCLUSION

Based on the present findings, it can be concluded that both Plant-O-Meter and GreenSeeker optical sensors are valuable, efficient, reliable, and useful tools for assessing nitrogen application and predicting wheat grain yield across different growth stages. Close readings obtained from portable sensors suggest that the use of NDVI sensors could be a crucial tool for optimizing application of nitrogen fertilizer in wheat. This research has significant implications for development of precision agriculture, promoting more efficient resource utilization and reduced environmental impact. The correlation of data obtained from GreenSeeker and Plant-O-Meter sensors was high, except during the plant maturation phase, when the correlation was negligible. A more in-depth analysis of two different varieties revealed a significant difference in the correlation between NDVI values and grain yield for the respective varieties. In the case of the Ingenio variety, a stronger correlation between NDVI values and grain yield was observed, reaching over 0.76% in certain phases. Throughout the entire vegetation period, the coefficients of determination were significant in predicting grain yield. This study aimed to compare the application of NDVI-measuring sensors, specifically the GreenSeeker and Plant-O-Meter. The GreenSeeker sensor, which focuses solely on the NDVI index, demonstrated a slightly stronger association with NDVI values compared to Plant-O-Meter. However, while the two devices showed only minimal differences in NDVI readings, it is important to note that Plant-O-Meter records in six distinct spectral wavebands and differentiates among spectral ranges. This capability enables generation of a large number of different vegetation indices, allowing more comprehensive vegetation monitoring and potentially diverse outputs. Nevertheless, both sensors provide a wide range of valuable information, allowing farmers to implement effective measures and management practices in the field to enhance yield and optimize the use of nitrogen fertilizer.

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