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Remote Sensing for Smart Agriculture – Monitoring Pepper Crops

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Abstract – **Remote sensing is an essential tool for modern agriculture, aiding in monitoring and managing crop health and productivity. This study focuses on assessing the ecological status of bell pepper crops (*Capsicum annuum*) using remote sensing techniques. It compares data from various sensors to identify the most effective tools for comprehensive crop assessment. The ultimate objective is to develop a reliable framework for remote monitoring, highlighting practical agricultural applications and improving the management and sustainability of vegetable crop production.**

Keywords – **NDVI, pepper crops, remote sensing, smart agriculture, vegetation indices.**

I. Introduction

Smart agriculture can leverage satellite and drone-based technologies to monitor and manage agricultural practices with high precision. Remote sensing can provide real-time data on crop health, soil conditions, and key environmental factors, enabling farmers to make informed and timely decisions [1, 2]. Within the sphere of smart agricultural practices, remote sensing technology plays a vital role by providing crucial insights into the growth, health, and dynamics of crops, as well as broader ecological and biodiversity conservation efforts.

This technology enables the assessment of crop development, yield estimation, and the overall management of agricultural processes, thereby contributing significantly to the field of precision agriculture. By providing data at varying spatial and temporal resolutions, remote sensing aids in both broad and detailed management of agricultural processes, optimizing resource use and enhancing sustainability.

In Bulgaria, the vegetable crops are grown on a relatively small cultivated area. Pepper is one of the most commonly planted vegetable in Bulgaria, along with the tomato. Vegetable production is a highly intensive and important subsector of agricultural production [3]. The National Research Programme "Smart Crop Production," underscores the importance of advancing digital and remote sensing techniques to foster sustainable and efficient food production systems.

The research is dedicated to investigate the advancement of remote sensing and digital techniques in agriculture to foster sustainable and efficient food production systems. This initiative centers on doing analysis of multispectral remote sensing images, utilizing digital image processing various algorithms to help identify key vegetation characteristics based on reflectance properties. One widely utilized metric is Normalized Difference Vegetation Index (NDVI), which offers valuable information on photosynthetic activity crucial for understanding overall vegetation vitality. Its simplicity in computation and broad applicability across different geographic scales and agro-climatic regions make it a fundamental tool for improved crop management. This technology enhances resource efficiency, optimizes yields, and supports sustainable farming by minimizing environmental impact [4].

A. Study area

The study area is located in the village of Katunitsa, within Sadovo municipality, which is located in the Plovdiv region in the south-central part of Bulgaria (Fig.1).

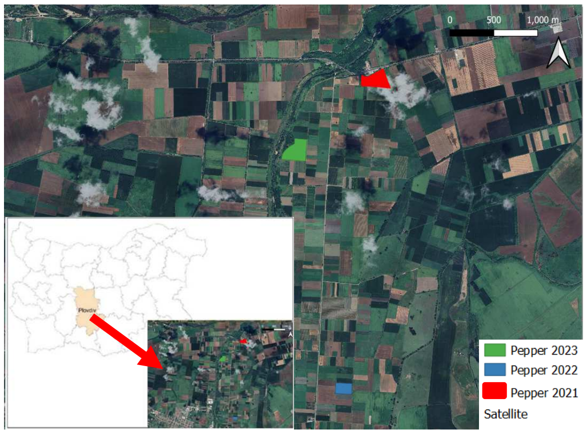

Fig. 1. Location of the pepper fields used for this study in 2021, 2022 and 2023 growing seasons

The focus of the research is on agricultural fields growing pepper (*Capsicum annuum*), which are cultivated in single

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rows, a standard planting arrangement, with a typical drip irrigation system (Fig. 2).

Fig. 2. Planting arrangement for the pepper crops

In the first year of the study, the field covered an area of 43 decares. In the second year, the field was smaller in size 22 decares, and in the third year, the field expanded significantly to 50 decares. The three fields selected for this study are situated very close to one another, which ensures that the crops are grow under similar environmental conditions. These conditions include comparable microclimate, consistent irrigation practices, uniform sunlight exposure, and other essential environmental factors that could influence crop growth and productivity.

II. Data and Methods

A. Processing

For the purpose of the study, preliminary data have been collected for the three pepper fields for the years 2021, 2022, and 2023. High-resolution (HR) images were acquired from Sentinel-2 satellite [5] for each of the five phenological stages of the pepper development. While Sentinel-2 data are easily accessible, free, and offer good temporal resolution, their spatial resolution is less suitable for monitoring small agricultural plots. To overcome this limitation, very high-resolution (VHR) satellite imagery was obtained from WorldView-3 [6]. Additionally, aerial imagery was captured using an unmanned aerial vehicle (UAV) − DJI Phantom 4 Multispectral. The use of UAV and VHR imagery is crucial for providing the detailed spatial resolution [7] necessary for monitoring small-scale crops (Fig. 3).

Fig. 3. Comparison of the different spatial resolution on the used data: From left to right Sentinel-2, 10m; WorldView-3, 0.31m; UAV, 0.03m

The research methodology encompasses several key steps: acquiring high-resolution satellite images, conducting UAV flights for detailed field imaging, processing and analyzing the collected data, and correlating remote sensing data with phenological observations and ground truth measurements. Specific algorithms were employed to process the data and derive various vegetation indices, such as the Normalized Difference Vegetation Index (NDVI). The satellite imagery underwent standard processing to extract vegetation indices and plant biophysical parameters, which were then used to evaluate and monitor the pepper fields.

This comprehensive approach combines satellite and UAV data to provide a detailed analysis of the crop health and development. The integration of these diverse data sources aims to enhance the accuracy of remote sensing in agricultural monitoring, offering valuable insights into crop management practices and productivity assessment.

Table 1. Satellite/UAV specifications

Satellite/UAV	Spatial resolution (m)	Radiometric resolution (Bits)	Swath (km)
Sentinel-2	10	16	290
WorldView-3	1.24	11	13.1
DJI Phantom 4 Multispectral	0.03	8	-

By employing both Sentinel-2 and WorldView-3 imagery, along with UAV data, the study ensures a robust monitoring framework. The high temporal resolution of Sentinel-2 complements the fine spatial resolution of WorldView-3, while UAV imagery offers additional granularity and flexibility. This multi-faceted data collection strategy is essential for capturing the dynamic growth stages of peppers and for developing precise, data-driven agricultural practices.

B. Vegetation indices

Vegetation indices (VIs) are optical measures that quantify the "greenness" of a vegetation canopy, which is influenced by factors such as leaf chlorophyll content, leaf area, canopy cover, and structure, along with biophysical processes like photosynthesis and transpiration [8]. As fundamental tools in remote sensing, VIs provide critical insights of crop conditions and the identification of potential stress factors, which is essential for effective agricultural management. They are used to determine vegetation status, track phenological changes, assess biomass, and more. By enabling accurate monitoring of vegetation dynamics and early detection of stress, VIs support timely interventions, ultimately enhancing crop productivity and sustainability [9].

VIs are based on the spectral characteristics of the vegetation, with most of them utilizing the strong absorption in the red and reflectance in the near-infrared (NIR) region of the electromagnetic spectrum (Fig. 4). The red region is associated with chlorophyll absorption, while the NIR region reflects the leaf structure [10]. Through various mathematical formulations—such as ratios, normalized differences, and weighted sums—these indices offer unique perspectives on canopy properties and underlying processes.

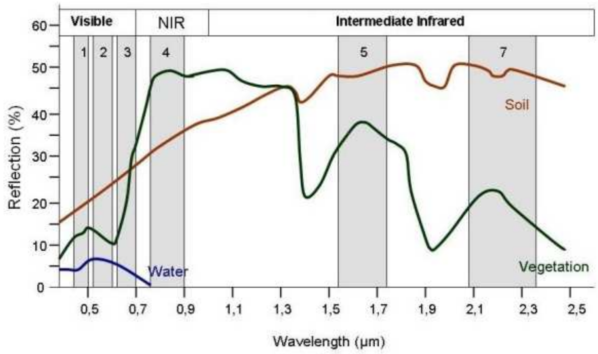

Fig. 4. Spectral reflectance characteristics [9] of green vegetation .

One of the most widely used VIs is the Normalized Difference Vegetation Index (NDVI) [11]. It is based on the difference between the maximum absorption in the red spectral range and the high reflectance in the near-infrared range of plants. It is defined as:

$$NDVI = \frac{NIR - RED}{NIR + RED}, \tag{1}$$

Where: NIR and RED are the values of signals in the near-infrared and red regions, respectively.

The NDVI, first developed by Rouse et al. [12], normalizes the data to reduce topographic and atmospheric influences, making it a reliable tool for large-scale ecological assessments and agricultural monitoring. NDVI values range from -1 to +1, with higher values indicating dense vegetation, low but positive values representing soil, and negative values corresponding to water due to its strong NIR absorption. This index helps in accurately tracking vegetation dynamics and identifying potential areas of stress, thereby supporting effective management practices and decision-making in agriculture monitoring [11].

To assess potential differences in the results, we compared the central wavelengths and half-widths of the Red and NIR bands across the sensors used in this study (Table 2). The comparison revealed that the central wavelengths differ by no more than 10 nm between the sensors. Given this minimal variation, we determined that any resulting discrepancies in the calculation of the vegetation indices are likely negligible, and thus, the impact on the overall accuracy of the indices is not significant.

TABLE 2. SATELLITE AND UAV CENTRAL WAVELENGTHS FOR RED AND NIR BANDS

Sensor	Central wavelength (nm) Red	Central wavelength (nm) NIR
UAV	560±16	840±26
WorldView-3	660±35	833±43
Sentinel-2	665±18	842±10

Theoretical analyses and empirical studies have demonstrated that VIs, particularly NDVI, are near-linearly related to the photosynthetically active radiation absorbed by the plant canopy. This relationship underpins light-dependent physiological processes, such as photosynthesis and transpiration, occurring in the upper canopy. Time-series analyses using VIs have been applied to measure primary production and evapotranspiration, although their accuracy is contingent on the quality of ground-truth data used for calibration.

III. RESULTS

NDVI values were calculated for each year's image (2021, 2022, 2023). The analysis revealed a wider range of NDVI values across all three years compared to what was initially observed.

Fig. 5. Vegetation index NDVI applied on UAV images, pepper field (2021)

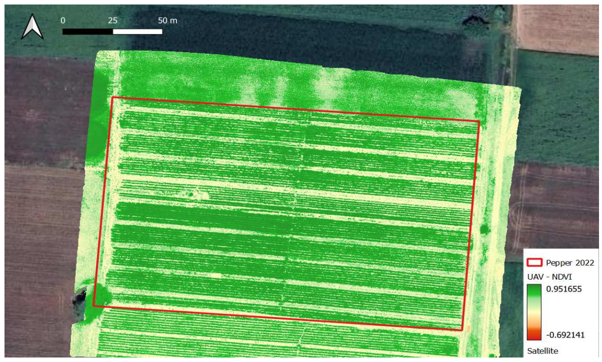

Fig. 6. Vegetation index NDVI applied on drone imagery, pepper field (2022)

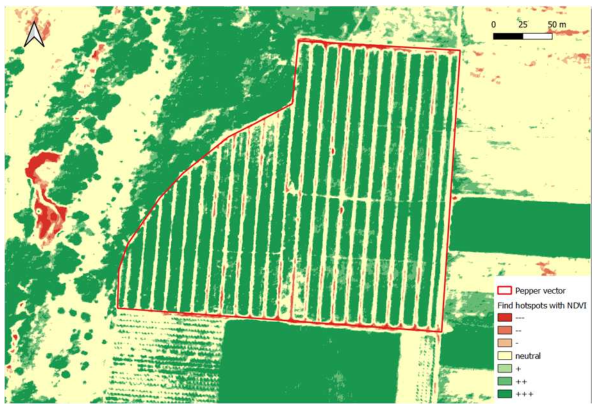

Fig. 7. Hotspots for vegetation index NDVI applied on satellite imagery from WorldView-3, pepper field (2023)

In 2021, the NDVI ranged from -0.5 (minimum) to 0.94 (maximum), with an average of 0.72.

The NDVI values in 2022 showed a similar spread, ranging from -0.7 (minimum) to 0.95 (maximum), with an average of 0.68.

Interestingly, 2023 exhibited the highest maximum NDVI value (0.84) but also the lowest minimum NDVI value (-0.27) compared to the other two years. The average NDVI for 2023 was 0.60.

To visually compare NDVI distribution across the years, side-by-side NDVI images for 2021, 2022, and 2023 were created. Further analysis is needed to determine the factors influencing the observed variations in NDVI, particularly the lower minimum NDVI value in 2023.

IV. Conclusion

The study demonstrated the potential of remote sensing techniques in smart agriculture, particularly for assessing plant growth and monitoring vegetable crops. By integrating satellite and UAV data, the research developed a framework for the remote monitoring of agricultural fields, highlighting practical applications that enhance the management and sustainability of agricultural production.

An additional distinction is obtained as a result of spatial resolution

The correct interpretation of remote sensing data, specifically through the use of vegetation indices, like the Normalized Difference Vegetation Index (NDVI), can significantly benefit agronomists. NDVI correlates directly with vegetation productivity, making it a valuable tool for various ecological and agricultural applications. By providing insights into the spatial and temporal distribution of vegetation communities, biomass, CO2 fluxes, and land degradation, NDVI aids in making informed decisions that mitigate extraction damage, optimize fertilizer use, and protect the environment [13].

Throughout the study, vegetation indices were generated, retrieved, compared, and analyzed alongside in situ observations and measurements during different growth stages of pepper. This analysis allowed for the proposal of a draft methodology tailored to the study of vegetable crops, laying the groundwork for more precise and efficient agricultural practices.

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