Plant and Soil Science

Journal homepage: https://agriculturalscience.com.ua/en
Plant and Soil Science, 16(4), 57-70
Received: 30.05.2025 Revised: 24.10.2025 Accepted: 27.11.2025

UDC 633.11:543.42
DOI: 10.31548/plant4.2025.57

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Varietal spectral differences in winter wheat plants according to satellite monitoring data

Abstract. The paper reflected the results of investigating the spectral features of winter wheat plants of various varieties, which was a component of the implementation of conventional remote monitoring technologies in precision agricultural production. It was based on empirical data for determining the characteristic spectral characteristics of different varieties and evaluating them using remote sensing data (RS). The purpose of the study was to establish the possibility of identifying varietal differences of winter wheat based on the spectral characteristics of plants obtained from open sources of satellite monitoring data. For this purpose, open data from the Sentinel-2 satellite was used, which provided relatively high spatial and spectral resolution. The analysis covered key wheat growing periods, and spectral differences were investigated using the RGB additive colour model and vegetation indices SAVI (soil-adjusted vegetation index), NDVI (normalised difference vegetation index), ARVI (atmospherically resistant vegetation index). The results of the study indicated the presence of significant spectral differences between winter wheat varieties due to their genetic diversity and response to agroecological conditions. It was found that spectral profiles and indices of photosynthetic activity of different varieties correlated with indicators of productivity and resistance to biotic and abiotic stresses. The obtained data helped not only to differentiate wheat varieties by spectral characteristics, but also to use them to

Suggested Citation:
Pasichnyk, N., Dmytrenko, O., & Petrenko, M. (2025). Varietal spectral differences in winter wheat plants according to satellite monitoring data. *Plant and Soil Science,* 16(4), 57-70. doi: 10.31548/plant4.2025.57.

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build models for predicting yield and evaluating adaptive properties in climate change conditions. The informative value of satellite data for optimising winter wheat cultivation technologies and improving the efficiency of breeding programmes was shown. Such studies were promising in the development of precision agricultural production technologies, ensuring prompt and objective assessment of the state of crops over large areas, tracking the phenology of a particular wheat variety, and in breeding research

Keywords: winter grain crops; varietal differences; remote monitoring of agrophytocoenoses; vegetation indices; spectral characteristics of plants

INTRODUCTION

Accurate observation of wheat phenology in close real time is critical for both agricultural technologies and breeding programmes. It allows effectively managing crops, choosing the most productive varieties, increasing grain yield and quality, and provides a scientific basis for sustainable wheat production. Remote sensing (RS) technologies, data digitisation, and big data management are finding practical application in crop production and therefore require methodological support. Management of agrophytocoenoses has acquired new approaches, agronomists need means of monitoring the state of crops, the quality and timeliness of technological operations, especially in large areas. Winter wheat crops require constant research for each new variety, considering biological features, noticeable differences in plant colour, and the reaction to agroecological factors. A separate important criterion remains the organogenesis of various varieties of winter wheat, depending on the time of sowing and growth conditions, considering the widespread late harvesting of predecessor crops. Remote satellite monitoring is relevant for solving this issue, which allows agricultural producers to receive constant updates about the situation in any field of the farm without the need for personal presence. The main advantage of satellite monitoring is the scale of the survey and the efficiency of data on the state of crops over large areas, which is several times different from ground-based measurements, which are local.

A. Zvonar (2020) presented a new approach to monitoring wheat phenology during the growing season using sequential RGB images and an integrated KNN-CNN-RF model. The researcher demonstrated that the combination of machine learning and deep learning algorithms allows accurately and timely determining the phenological phases of wheat, which is especially valuable for breeding programmes and crop management. The technique has proven its effectiveness in comparison with conventional approaches, providing higher accuracy and stability of results.

Methodologies for monitoring the phenology of cultivated plants, with the establishment of dependencies on external parameters, are based on the following criteria. Based on the plant parameters of the variety, as shown in the paper by U. Akumaga *et al.* (2023) that combined data from ground-based phenological studies with the leaf area index (LAI) obtained from satellite images of the Planet Fusion platform, also by R. Zhang *et al.* (2024) that proposed a two-step deep learning framework called PhenoNet for accurate and efficient classification of key wheat phenophases in real time. Based on spectral features: in their research papers on the description of crop phenology, the teams of researchers presented the results of selecting optimal variants of the shape model (SMF-S) based on the time series data of the vegetation index (Liu *et al.*, 2022). A model using the time series normalised difference vegetation index (NDVI) and normalised difference red edge index (NDRE) obtained from multispectral UAV images was able to accurately determine full ear emergence dates for more than 1,000 rice varieties (Liu *et al.*, 2023). Machine learning models were based on the characteristics of radar polarisation.

G. Song *et al.* (2022) presented an approach to monitoring leaf phenology in tropical rainforests using deep learning techniques. The researchers used super-pixel classification of time series of images of tree tents, which allowed improving the accuracy of tracking changes in vegetation. The results showed that artificial intelligence combined with remote images significantly improves the ability to assess the seasonal dynamics of plant development. This study is a valuable example of the use of modern image analysis algorithms for monitoring the state of crops and optimising agricultural technologies in accordance with the principles of precision farming. The paper by D. Cann *et al*. (2023) examined the role of phenology in the adaptation of winter wheat to various climatic conditions. The researchers showed that varying the duration of the development phases significantly affects the yield and stability of crop productivity in a variable environment. The study highlighted the importance of considering the phenological characteristics of varieties to improve the effectiveness of agricultural technologies and breeding programmes. These results are useful for precision farming, as they demonstrate the possibility of optimising fertilisation and crop management systems considering the biological rhythms of plants.

The purpose of the study was to determine the information content and feasibility of using images in the RGB additive colour model, vegetation indices NDVI, SAVI, ARVI for investigating varietal spectral differences in the agrophytocoenosis of winter wheat using remote sensing.

LITERATURE REVIEW

In crop production, variety replacement is a consistently relevant measure, and the latest technologies for monitoring agrophytocoenoses should consider this. Varietal spectral differences of even the most popular cultivated plants are poorly understood, but researchers continue to look for ways to obtain objective data. In studies of varietal differences of winter wheat in recent years, the main focus has shifted towards high – frequency phenotyping – the use of UAVs with multi-and hyperspectral sensors, a combination of ground-based spectrometers and satellite data, and the use of deep learning methods. Hyperspectral models for monitoring the chlorophyll density (ChD) of winter wheat were constructed using eight machine learning algorithms. A combination of algorithms for intelligent analysis of wheat plant traits and machine learning was used as a hyperspectral imaging system. J. Ma *et al*. (2022) reviewed the use of hyperspectral images to assess the protein content of wheat grains, summarised modern methods for collecting, processing, and analysing spectral data, highlighting the advantages of this technology over conventional laboratory approaches. The researchers noted the prospects of integrating hyperspectral systems into high-performance phenotyping and breeding programmes, and their importance for improving the accuracy of grain quality assessment in production conditions.

Crop growth models such as Crop-Grow, WOFOST, APSIM, and others predict crop phenology based on variety parameters and environmental conditions. However, their application is difficult due to the need to calibrate the parameters of each variety. This is most difficult to do for new varieties. Phenology can also be controlled based on polarised traits that are sensitive to the morphological parameters of crops. D. Vincke *et al*. (2022) proposed a combination of crop shape and growth models for determining the phenological phases of soybeans. The method demonstrates promise for monitoring field crops in precision farming. The authors used near-infrared hyperspectral imaging to assess the presence of grains in wheat ears. This approach allows improving the accuracy of yield forecasting. R. Zhang *et al*. (2024) developed the lightweight two-step PhenoNet neural network for real-time classification of wheat phenological phases, making it convenient for agricultural practice. A. Zvonar (2020) proposed a method for monitoring wheat phenology for breeding tests using a combination of KNN-CNN-RF models based on RGB images. The solution is effective for analysing a large number of samples. J. Campoy *et al*. (2023) created a remote sensing model for predicting wheat and barley yields that works both at the level of field and within the field, improving the accuracy of productivity estimates.

Multispectral cameras in combination with time series allows tracking growth dynamics, are used for crop forecasting and classification of varieties, and operational monitoring of large areas. Thus, X. Lyu *et al.* (2024) used aerial (UAV-hyperspectral) images to distinguish between winter wheat varieties and deep learning (ENVINet5) and SVM methods to process the data. The conducted studies showed a close relationship (R2 to ≈ 0.96), and the developed method was recommended for classifying the varieties under study. However, the proposed method has limitations in the area of application and requires specialised ground equipment and, accordingly, trained specialists. The use of satellite survey data to study various indicators of agrophytocoenoses of winter wheat showed both positive and unsatisfactory results. W. Cai *et al.* (2022) presented a new multiple phenological spectral trait (Mpsf) for mapping winter wheat. The researchers used multi-phenological indices: NDVI, $NDVI_6$, GNDVI (Green NDVI), EVI (Enhanced Vegetation Index), BSI (Bare Soil Index), PSRI (Plant Senescence Reflection Index) to search for objective identification of wheat and individual other crops, and integration of the main growth phases. Important, according to the researcher, are the presented results of studies of the informative value of individual Sentinel2 spectral channels to evaluate wheat growth: rededge 705 and 740 nm, near-infrared NIR 783, 865 nm, calculated LAI indices (Revill *et al.*, 2019); VSWIR multispectral and hyperspectral data (Pancorbo *et al.*, 2025). It was shown that the red-edge/SWIR, NDSI indices significantly increase the accuracy of assessing the biophysical properties and yield of the variety. Varieties can have different photopigmentation and structural properties of plants. The spectral features of plants were considered by researchers in the study of nitrogen supply, with the analysis of protein content of the resulting grain (Camino *et al.*, 2018; Aranguren *et al.*, 2020). The micronutrient nutrition was considered in the study of the potential of hyperspectral imaging. Grain quality prediction models based on the spectral reflectivity of flour showed very promising results (r2 > 0.60) for Mg, Mo, and Zn (Hu *et al.*, 2021).

Based on Sentinel-2 time series and indices a method for classifying plant stresses was developed, which allowed, in particular, distinguishing diseased plants from nitrogen deficiency (Shi *et al.*, 2023). The researchers noted the possibility of using this method for varietal differentiation, if varieties respond differently to stress. Hyperspectral data were used for early diagnosis of biological stress in wheat plants, characteristics that determine grain quality and moisture content (Xie *et al.*, 2024; Wang *et al.*, 2024; Sun *et al.*, 2025).

Therefore, previous studies have shown the feasibility of using satellite remote sensing methods, which opens up prospects for timely detection of stress factors, assessment of organogenesis dynamics, and ensuring effective management of agrophytocoenoses over large areas. Varietal spectral characteristics were studied mainly from ground platforms and UAVs, which has advantages in accuracy, but loses scale and availability. The question remains of developing a scientific basis for improving technologies for growing winter wheat and increasing its productivity in the precision farming system. Scientific data indicate the relevance and prospects of studying the spectral varietal features of winter wheat, and the informative value of such characteristics for solving practical technological problems.

MATERIALS AND METHODS

Studies of wheat growth and development were conducted during two seasons – 2021 and 2022 and performed on production areas occupied by winter wheat. The field with a total area of 40.5 hectares was located in the Boryspil District of the Kyiv Oblast, near the national highway H08. Four varieties of winter wheat were grown within the field, as shown in Figure 1: 'Tobak' (9.8 ha), 'Akhim' (9.2 ha), 'Milton' (6.8 ha), and 'Royal' (6.2 ha). Varieties 'Tobak' and 'Akhim' are modern medium-ripened (growing season 270-280 days) varieties of soft, awnless winter wheat, lutescence variant, intensive type, produced by German company Saaten-Union. 'Milton' and 'Royal' varieties are intensive medium-early winter wheat varieties, an erythrospermum variant, produced by Canadian origin (Seed Grain Company).

Figure 1. Field location (coordinates 50°27'33"N 31°00'34"E; left) and winter wheat varieties (right)
Note: 'Tobak', 'Akhim', 'Milton', 'Royal'
Source: Google Earth (n.d.)

Reproduction of varieties – elite. Potatoes were the predecessor crop, allowing wheat to be sown on time. The topography of the field was mostly flat, which eliminates the cancellation of growing conditions. The soil cover and technical background of the agrophytocoenosis were uniform, which enabled a comparison of exclusively varietal differences. The EOS Land Viewer platform of the European Space Agency (ESA), which is part of the space mission for remote sensing of the Earth, specialised for crop production tasks was used to perform satellite monitoring. Images of the Sentinel 2 satellite obtained from the Copernicus Open Access Hub (DataHUB) archive were used. The Sentinel-2 was equipped with the MSI multispectral Instrument, which provided shooting in 13 spectral channels with a spatial resolution of 10, 20, and 60 m and a repeat cycle of about 5 days. The choice of this satellite was conditioned by its free access to data, the highest spatial resolution of images among available satellites (10m/pixel). The use of various indices helped to comprehensively assess the state of crops and spatial heterogeneity of the field. The study used combinations of spectral channels that are most sensitive to changes in plant photosynthetic activity and chlorophyll status: B4 (Red, 665 nm, 10 m) – chlorophyll uptake; B8 (NIR, 842 nm, 10 m) – leaf cover reflection; B5, B6, B7 (Red Edge, 705–783 nm, 20 m) were additionally used to assess the physiological state of plants. Vegetation indices were calculated based on these channels, in particular: NDVI (B8 – B4/B8 + B4), SAVI (B8 + B4 + L (B8 – B4) · (1 + L)), ARVI (B8 + (B4 – γ · (B4 – B2))B8 – (B4 – γ · (B4 – B2))). This combination of spectral channels and vegetation indices helped to track the growth characteristics of winter wheat at different stages of vegetation and assess the spatial heterogeneity of crops.

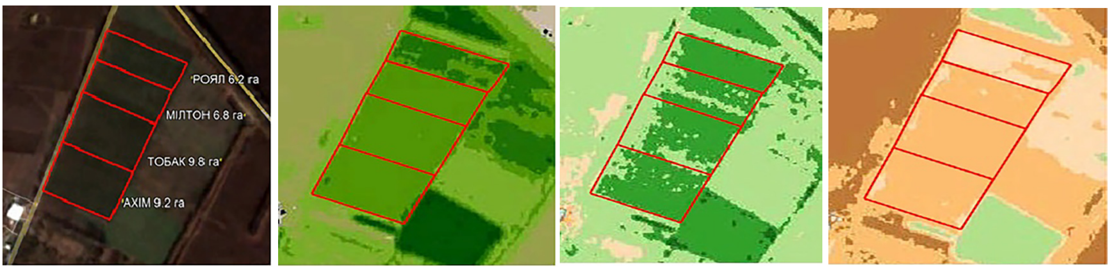
Satellite image dates were selected considering the local time zone (UTC + 2 / UTC + 3), minimal cloud cover, and compliance with key phenological phases of winter wheat development. In the autumn period (germination and tillering, BBCH 10-29), indices were analysed to assess the density of seedlings, uniformity of development, and the influence of stress factors at the initial stages of growth. In the spring period (stem elongation – heading, BBCH 30-59), the main attention was paid to the dynamics of indices reflecting photosynthetic activity and chlorophyll content, as well as to monitoring the water status of plants. The assessment of plant condition based on satellite images was carried out by the author as an expert. Before processing the data, atmospheric correction (L2A level, Bottom-of-Atmosphere) was performed, which reduced the impact of atmospheric conditions on reflection, including georeferencing and cloud masking using the Scene Classification Layer (SCL) built into Sentinel-2 products.

Verification of compliance of the results was carried out by ground-based morphological and biometric studies (BBCH stages, visual assessment of the state of crops, features of soil cover and microrelief). The growing season of the territory was determined by the transition of the average daily temperature through 5°C, as accepted in crop production. This approach helped not only to identify varietal differences in the dynamics of vegetation indices, but also to identify the influence of soil and technological factors on the heterogeneity of the field. The study was conducted in accordance with the ethical standards of Convention on Biological Diversity (1992) and Convention on the Trade in Endangered Species of Wild Fauna and Flora (1976).

RESULTS AND DISCUSSION

For the completeness of spectral analysis of winter crop agrophytocoenoses within the framework of remote monitoring, the author suggests it is appropriate to use data from the autumn and spring periods of winter wheat vegetation. Autumn vegetation, according to scientific data, should last 40-60 days, so that the plants have time to gain the necessary amount of effective temperatures (300-350°C) before the end of the growing season, that is, a stable transition below 5°C. Due to the completeness of the autumn growing season, plants have time to accumulate the necessary amount of plastic substances for the wintering period, which increases their stress resistance.

In the experimental field, plants entered winter in the initial early tillering stage (BBCH 20). Figure 2 shows images of the autumn vegetation of winter wheat, at the time of the first ground survey and plant accounting. The plants were in the leaf development phase (BBCH 10). The first image shows the state of plants in the visible spectrum. Sparse vegetation with the presence of open ground was identified. Light spots are clearly distinguished on the varieties 'Milton' and 'Royal', which can be explained by the soil heterogeneity of the part of the field they occupy.



RGB | NDVI | ARVI | SAVI

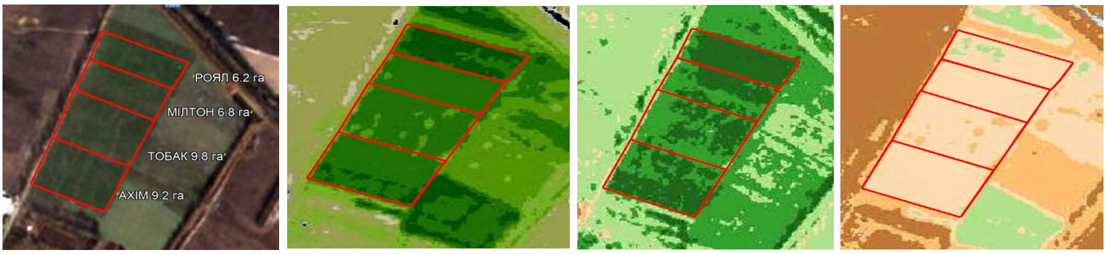
Figure 2. Index images of satellite survey data of winter wheat agrophytocoenoses (BBCH 10, survey date 13.11.2021)

Note: 'Tobak', 'Akhim', 'Milton', 'Royal'; RGB – additive colour model; NDVI – normalised difference vegetation index; ARVI – atmospherically resistant vegetation index; SAVI – soil-adjusted vegetation index

Source: EOS data analytics (n.d.)

Analysis of index images showed that the 'Royal' variety differed from others in higher values. Homogeneous elementary plots for each variety were used to compare the index values. This characteristic NDVI value for the 'Royal' variety was 0.38, for other varieties it was 0.31-0.33. This allowed assuming that this variety is characterised by a more intensive beginning of growth processes at the autumn stage of vegetation. Reflection of a high index indicator on a plot with the 'Royal' variety was observed for 80-85% of the territory. Ground-based phenological studies have established that it was on the site under the 'Royal' variety that the density of the projection vegetation cover was 32-38, for other varieties in this field – it did not reach 30%. This explains the low information content of NDVI, because this index is sensitive to projective vegetation cover.

ARVI, which is not very sensitive to atmospheric factors (such as aerosols), was chosen for data analysis due to its ability to adjust for autumn weather conditions. Compared to other vegetation indices, its values were most variable, in particular in the areas of the varieties 'Achim', 'Tobak', and 'Milton'. The largest gradient of the index values was observed for the varieties 'Tobak' and 'Milton', ground-based studies did not show a correlation of these differences with the topography of the territory, and therefore, it is possible to assume that they are conditioned by spectral characteristics. Attention is drawn to the special feature of the ARVI and SAVI index images of land plots near the forest belt. The values of these indices in such marginal zones were poorly correlated with ground-based biometric studies, so, in the according to the author, marginal zones should not be considered in the spectral analysis of agrophytocoenoses. The total coverage of the agrophytocoenosis in these two indices for the varieties 'Achim', 'Tobak', and 'Milton' in the SAVI index was uniform. There is a clear reflection of soil or technological heterogeneity for the 'Milton' variety in the form of a strip, which later, in May, became more noticeable. Satellite monitoring of the state of agrophytocoenoses is almost not used in winter due to weather conditions, a pause in the growing season of the crop, and therefore low relevance. The availability of a clear image without snow cover allowed analysing the agrophytocoenosis in its winter dormancy state, which was done on 2 January 2022. The results are shown in Figure 3.



RGB NDVI ARVI SAVI

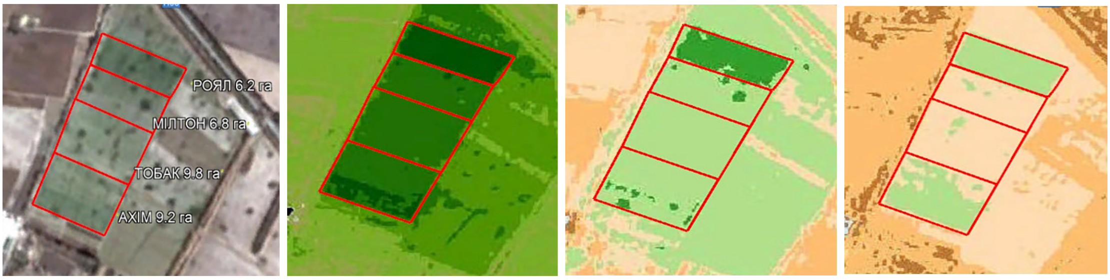
Figure 3. Satellite monitoring of winter wheat crops in the tillering phase (BBCH 20, survey date 02.01.2022)

Note: 'Tobak', 'Akhim', 'Milton', 'Royal'; RGB – additive colour model; NDVI – normalised difference vegetation index; ARVI – atmospherically resistant vegetation index; SAVI – soil-adjusted vegetation index

Source: EOS data analytics (n.d.)

The image in the visible part of the optical spectrum with a uniform green colour reflects the steady development of winter wheat varieties. In terms of NDVI value, the leadership was maintained by the 'Royal' variety – approximately 80% of the area, the index value was higher compared to other varieties. Varieties 'Milton' and 'Tobak' had a more uniform index coverage, but on the part of the field with these varieties, relief differences ("saucers") were clearly traced, where plants with significantly worse development were identified. The development of zones of higher indices for the variety 'Achim' was noted. According to the results of the construction of ARVI, the leading position was occupied by the 'Royal' variety. Other varieties had visually similar index values, and soil heterogeneities are reflected. Plants of other varieties, except 'Royal', developed worse in areas near the forest belt. In second place in terms of Index indicators was the 'Achim' variety. Spectral analysis showed low information content of SAVI for the task at hand. This is conditioned by the specifics of its work with poorly visible soil at this stage, although the "falling" terrain zones on the 'Tobak' variety are quite clearly identified.

During the spring resumption of wheat vegetation, it is difficult to assess the state of production areas of agrophytocoenoses, namely, the number of damaged plants, the tillering coefficient, the rate of active growth for planning agricultural operations, etc. The date of the first spring monitoring, based on the quality of the satellite images received, was set for 23 March 2022. The conditions of the month allowed plants to begin spring tillering, and the warming at the end of March – beginning of April became a factor in the resumption of vegetation (Fig. 4).



RGB NDVI ARVI SAVI

Figure 4. Satellite monitoring of winter wheat crops in the tillering phase (BBCH 20, survey date 23.03.2022)

Note: 'Tobak', 'Akhim', 'Milton', 'Royal'; RGB – additive colour model; NDVI – normalised difference vegetation index; ARVI – atmospherically resistant vegetation index; SAVI – soil-adjusted vegetation index

Source: EOS data analytics (n.d.)

The visible spectrum shows that most of the area of the 'Royal' variety has a relatively greener colour. In the field, changes in the terrain are noticeable in the form of depressions, the so-called "saucers". Soil heterogeneity is visually apparent In addition, for the 'Achim' variety, there is a zone (about 25% coverage) with higher index indicators. Comparing the index values with the data of 02.01.22, it can be concluded that the plants are at rest or that the slow passage of spring tillering processes is not available for satellite recording. Considering the distribution of the NDVI index, the active development of crops of the 'Royal' variety and ¼ part of the 'Achim' variety plot is clearly reflected. The existing zone of more active plant development in the 'Achim' variety has a sharp transition, which indicates technological reasons. Varieties 'Milton' and 'Tobak' develop uniformly, without dividing into zones. The ARVI vegetation index also showed the most active development of plants of the 'Royal' variety and part of the 'Achim' variety plot for the period of the end of March. There is a noticeable active development of areas with a decrease in the 'Milton' variety, which explains the presence of more moisture. Analysing the SAVI indicators, which consider the presence of soil in the image, a similar distribution of areas with active vegetation by variety was obtained: the most developed varieties are 'Royal' and 'Achim', and the area of more productive zones on the site of the latter variety increased to 75%.

The next remote monitoring date was May 7, 2022. Due to cloudy and rainy weather in April, monitoring was not carried out, and a similar problem was observed in May. A special feature of this period is the intensive growth of plants, in fact, the approach of plants to the peak of vegetative mass development. Wheat at the stage of stem elongation (BBCH 30), actively growing, plants of bright green colour. For photosynthesis, the amount of solar activity at this time is sufficient. Agrophytocoenosis is aligned by spectral characteristics. For this time of monitoring, the visible spectrum image turned out to be more informative than the index ones. The picture shows a clear difference in the colour of the 'Milton' variety, compared with others: the plants have a lighter colour. Considering the yield of this variety later, the authors were convinced of the assumption that the colour of the plants was associated with its physiological characteristics, and not with low photosynthetic activity. As a result of constructing the SAVI index, a well-defined green band was obtained on the 'Milton' variety, which correlates with the images of previous monitoring and may be associated with changes in terrain and better water supply.

The next observation of the condition of winter wheat plants was carried out on 21 June 2022 during the flowering phase – grain formation (BBCH 60-70). The NDVI values were relatively higher for the varieties 'Achim' and 'Tobak', but the specifics of plant colour during this growing season should be considered.

Varieties 'Royal' and 'Milton' have earlier maturation periods, because they developed faster by several microstages of BBCH, which was proved by biometric records. The dynamics of the NDVI value during the entire monitoring was presented graphically (Fig. 5).

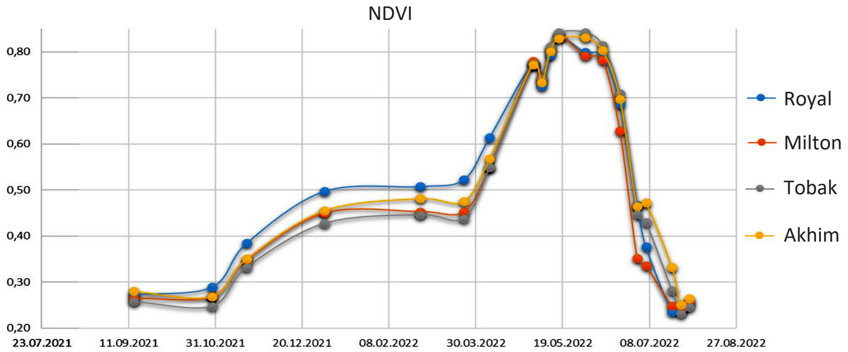


Figure 5. Graph of distribution of NDVI index values of different winter wheat varieties, 2022
Note: 'Tobak', 'Akhim', 'Milton', 'Royal'; NDVI – normalised difference vegetation index
Source: EOS data analytics (n.d.)

SAVI analysis fully confirmed the distribution of sites according to the intensity of photosynthetic activity of the leaf apparatus. The leaders are the varieties 'Achim' and 'Tobak'. Plants in all areas were delayed in growth in areas near the forest belt. The filling of winter wheat grains is closely linked to the activity of the photosynthetic apparatus of the flag leaf. The importance of remote monitoring at this time is extremely high. The information that can be obtained about the state of crops will indicate the physiological characteristics of varieties regarding the duration of active activity of the flag leaf. Even after analysing the visible spectrum image, one can see a change in the colour of all varieties, namely a decrease in the intensity of the green colour. It is noticeable that the 'Milton' variety has the lightest colour.

According to NDVI, areas of the 'Royal' and 'Milton' varieties are distinguished, which have a low level of vegetation, in contrast to small areas of low relief, where there is a delay in development. It should be noted that the beginning of a decrease in the value of the NDVI index for other varieties ('Tobak', 'Achim'). Thus, for the 'Achim' variety, the zones of low vegetation are 50%, and for the 'Tobak' variety – 35-40%. For comparison, the area of such zones for 'Royal' is 70%, and for 'Milton' – 85%. According to ground-based studies, approximately 85% of plants of the 'Milton' variety as of 21 June 2022 were in the stage of grain formation, the second place was taken by the 'Royal' variety (67%), and flowering was completed in other varieties.

Consequently, index images of satellite monitoring data made it possible to identify early-maturing varieties 'Royal' and 'Milton' with the greatest manifestation in the latter. At the next stage of monitoring (06.07), the activity of the photosynthetic apparatus of both varieties almost did occur, plants are approaching the end of the grain maturation phase (Fig. 6). Photosynthetic activity of the upper tier of 'Tobak' and 'Achim' varieties was also observed at this time, judging by the distribution of vegetation indices. This suggests that the accumulation of a larger amount of active temperatures may affect the amount of assimilating substances in the grain and further affect its qualitative composition.

The results of the conducted studies confirmed the conclusions of X. Liu *et al.* (2023) that a hyperspectral remote sensing system can potentially be used to classify winter wheat varieties, and it provides a benchmark for classifying crops with weak intra-class differences. However, the researchers investigated the spectral differences of wheat from the UAV platform. Satellite monitoring has fundamentally different parameters, especially for free access data, but in terms of efficiency, scale, and availability, it significantly exceeds all other types. The results obtained showed the informative nature of satellite data for determining varietal differences, and therefore the prospects of such an area. High information content of multispectral images of Sentinel-2B was shown by M. Memon *et al*. (2023) to accurately estimate and map the percentage of wheat straw cover WSC compared to Landsat-8 data in a large-scale agricultural region. The researchers support their results with improved temporal and spatial data, but do not distinguish between wheat varieties. W. Cai *et al*. (2022) developed and used the generated new multi-factor spectral features as output data for the ONE-Class Support Vector Machine (OCSVM) for mapping winter wheat. However, the developed system showed positive results for phenological studies, without distinguishing wheat varieties or varietal types. Similar conclusions were also made by R. Zhang *et al*. (2024), who noted that combining multispectral satellite data with machine learning significantly improves the accuracy of crop condition identification and crop yield estimation.

RGB NDVI ARVI SAVI

Figure 6. Satellite monitoring of winter wheat crops in the tillering phase (BBCH 80, survey date 06.07.2022)

Note: 'Tobak', 'Akhim', 'Milton', 'Royal'; RGB – additive colour model; NDVI – normalised difference vegetation index; ARVI – atmospherically resistant vegetation index; SAVI – soil-adjusted vegetation index

Source: EOS data analytics (n.d.)

O. Tarariko *et al*. (2019) noted a significant differentiation of the reflective characteristics of crops in the ear emergence phase and full ripeness, which allows identification based on remote survey materials. Hyperspectral imaging (narrow bands, near and middle parts of the infrared spectrum – NIR/MIR) allows the most accurate detection of spectral differences between varieties, especially in critical phenophases (stem elongation – flowering). Free access satellite technologies have a number of limitations. Compared to shooting with UAVs, the data has a fundamentally lower ability to distinguish images and is limited in use in the presence of clouds. Therefore, it is appropriate to use the opportunity to conduct a series of experiments due to the large coverage area and calibrate the data based on ground measurements (Opryshko *et al*., 2024). Previous studies of the spectral characteristics of plants have established dependencies, formed a hypothesis about the possibility of developing vegetation indices based on an alternative model of colour formation, which will be more resistant to changes in lighting.

Thus, the results of the conducted research confirmed that Sentinel-2 satellite multispectral data can be an effective tool for classifying wheat varieties, providing an optimal balance between accuracy, scale, and availability of monitoring. Satellite monitoring allowed assessing the growth dynamics and development of winter wheat varieties, identify early-maturing varieties and reflect spatial heterogeneities of the agrophytocoenosis. NDVI, ARVI, and SAVI data confirmed their informative value for varietal differentiation, although they are inferior in resolution to hyperspectral UAV images. Together with ground-based measurements, satellite data provide a large-scale and operational tool for precision farming, which allows assessing the condition of crops in a timely manner and predicting yields.

CONCLUSIONS

Monitoring with Sentinel-2 helped to identify winter wheat varieties by spectral differences that occur at different stages of vegetation. The recorded stable spectral signatures allowed working remotely with individual varieties of winter wheat, in particular, to identify the stages of vegetation of different varieties. Interpretation of satellite data by EOS LandViewer through vegetation indices NDVI, SAVI, ARVI allowed assessing the general state of phytocoenoses of winter wheat and conducting phenological studies with reference to varietal characteristics. Thus, in the range of vegetation indices NDVI, SAVI, ARVI, the early beginning of autumn vegetation of the 'Royal' variety was established, which was confirmed by ground studies. The NDVI value for the 'Royal' variety was 0.38, for other varieties it was in the range of 0.31-0.33. Index maps and other vegetation indicators identified varieties with higher photosynthetic activity, which may be related to potential productivity and adaptability to climatic conditions. Thus, in the BBCH 80 stage (shooting date 06.07.2022) for early-maturing varieties of Canadian selection 'Royal' and 'Milton', the activity of the photosynthetic apparatus was not recorded, ground observations showed approaching the end of the grain maturation phase. Photosynthetic activity of the upper tier of German varieties 'Tobak' and 'Achim' continued, which showed the distribution of vegetation index values and was confirmed by ground-based studies.

The informative value of satellite monitoring for identifying varietal characteristics of winter wheat depended on the growing season. Regardless of the variety, during the stem elongation – beginning of ear emergence, the wheat agrophytocoenosis acquires a uniform intense green colour, varietal differences are visually recorded by ground surveys, but are practically not identifiable by satellite imagery. The results obtained confirmed the prospects of using satellite data for variety assessment and monitoring of agrophytocoenoses on a large scale, breeding work and digital agriculture, in particular in precision technologies. Further research, according to the authors, should be aimed at verifying satellite data with ground-based observations and refining processing algorithms to improve the accuracy of variety identification.

ACKNOWLEDGEMENTS

The authors would like to express their sincere gratitude to: LLC Biotech LTD (Boryspil District of Kyiv Oblast) for the opportunity to conduct field research in the production field and for providing information on winter wheat varieties and cultivation technology maps; the European Space Agency (ESA) for free access to satellite images; and Yevhen Ivanitsky, Master of Agronomy, for his assistance in conducting the research.

FUNDING

The research was initiated by the authors and did not receive funding.

CONFLICT OF INTEREST

None.

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Сортові спектральні відміни рослин пшениці озимої за даними супутникового моніторингу

Анотація. Стаття відобразила результати вивчення спектральних особливостей рослин пшениці озимої різних сортів, що є складовою імплементації традиційних технологій дистанційного моніторингу в технології прецизійного агровиробництва. В основу покладені емпіричні дані визначення характерних спектральних характеристик різних сортів та оцінка їх із використанням даних дистанційного зондування Землі (ДЗЗ). Метою роботи було встановити можливість ідентифікації сортових відмін пшениці озимої за спектральними характеристиками рослин, отриманими із відкритих джерел даних супутникового моніторингу. Для цього використовувались відкриті дані супутника Sentinel-2, які забезпечили порівняно високі просторову та спектральну роздільність. Аналіз охоплював ключові періоди вегетації пшениці, а спектральні відмінності досліджувались за допомогою адитивної колірної моделі RGB і вегетаційних індексів SAVI (soil-adjusted vegetation index), NDVI (normalised difference vegetation index), ARVI (atmospherically resistant vegetation index). Результати дослідження свідчили про наявність істотних спектральних розбіжностей між сортами пшениці озимої, що зумовлені їхньою генетичною різноманітністю та реакцією на агроекологічні умови. Встановлено, що спектральні профілі та індекси фотосинтетичної активності різних сортів корелювали з показниками продуктивності та стійкості до біотичних і абіотичних стресів. Отримані дані дозволили не лише диференціювати сорти пшениці за спектральними характеристиками, а й використовувати для побудови моделей прогнозування врожайності, оцінювання адаптивних властивостей в умовах змін клімату. Показано інформативність супутникових даних для оптимізації технологій вирощування пшениці озимої, підвищення ефективності селекційних програм. Такі дослідження є перспективними у розвитку технологій прецизійного агровиробництва, забезпечуючи оперативність та об'єктивність оцінки стану посівів на великих площах, відстеження фенології конкретного сорту пшениці, а також у селекційних дослідженнях

Ключові слова: озимі зернові культури; сортові відміни; дистанційний моніторинг агрофітоценозів; вегетаційні індекси; спектральні характеристики рослин