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Investigation of Disease-Yield Relationship of Yellow Rust in Some Bread and Durum Wheat Varieties by Phenological Periods Using Hyperspectral Data[A]

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Abstract: The aim of this study was to evaluate the severity of yellow rust in different phenological periods by subjecting bread (Bayraktar 2000, Demir 2000, Eser and Kenanbey) and durum (Çeşit-1252, Eminbey, Kızıltan 91 and Mirzabey 2000) wheat varieties to different spore doses (0%, 25%, 50% and 100%) under controlled epidemic conditions. The research was conducted in Yenimahalle, Ankara, Turkey during the 2018-2019 growing season. In the study, the morphological changes in yellow rust severity were determined at different phenological developmental stages of the test materials with the reflectance values obtained by using handheld spectroradiometer in different spore dose applications during the period from tillering to stalk emergence. These reflectance values were converted into vegetation index values expressed by mathematical formulae and used in determining yield estimates. Considering the results obtained, it was determined that the spectral indices calculated especially in the early flowering period (25 May 2019, Feekes 10.5.1) were effective in yield estimation for all bread varieties except Kenanbey variety (15 June 2019, Feekes 10.5.4). It was determined that the spectral band region of 25 May 2019 (Feekes 10.5.1), which includes all indices determined to predict yield in all bread and durum varieties and which is the beginning of flowering, was effective. In grain yield estimation,

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[A] This study was carried out by Metin AYDOĞDU in the master's thesis "Determination of the Seasonal Effects of Different Iron and Zinc Applications on Yellow Rust (*Puccinia striiformis* f. sp. *tritici*) Disease in Winter Wheat Using Multi-Band Data" at Kırşehir Ahi Evran University, Institute of Science, Department of Agricultural Biotechnology. (YÖK Thesis No: 671046/Date: 25.05.2021). This study does not require ethics committee approval.

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it was determined that there was a decrease in the correlation values of the spectral indices starting from the early flowering period (Feekes 10.5.1) towards the grain setting period (Feekes 10.5.3) and milk maturity period (Feekes 10.5.4). When the correlations between these index values and yield values were examined, it was determined that prominent phenological periods and high correlation indices could be calculated for these periods. Nowadays, with the use of optical sensor technology instead of traditional disease surveillance methods, the way has paved the way for the development of new approaches for early, fast and accurate yield estimation as a result of the verification of images taken by unmanned aerial vehicles on which multispectral and hyperspectral cameras are located with ground data using artificial intelligence and deep learning techniques.

Keywords: Hyperspectral data, spectral indice, wheat, yellow rust desease *(Puccinia striiformis* f. sp. *tritici),* yield estimate.

Bazı Ekmeklik ve Makarnalık Buğday Çeşitlerinde Sarı Pas Hastalığının Fenolojik Dönemlere göre Hastalık-Verim İlişkisinin Çok Bantlı *(Hiperspektral)* Veriler Kullanılarak Araştırılması

Özet: Bu çalışma, ekmeklik (Bayraktar 2000, Demir 2000, Eser ve Kenanbey) ve makarnalık (Çeşit-1252, Eminbey, Kızıltan 91 ve Mirzabey 2000) buğday çeşitlerini kontrollü epidemi koşullarında farklı spor dozlarına (%0, %25, %50 ve %100) tabi tutarak farklı fenolojik dönemlerde sarı pas şiddetini değerlendirmeyi amaçlanmıştır. Araştırma 2018-2019 yetiştirme sezonunda Yenimahalle, Ankara, Türkiye'de yürütülmüştür. Çalışmada, kardeşlenmeden sapa kalkmaya kadar olan dönemde farklı spor dozu uygulamalarında el spektroradyometresi kullanılarak elde edilen yansıma değerleri ile test materyallerinin farklı fenolojik gelişim dönemlerinde sarı pas şiddetindeki morfolojik değişimler belirlenmiştir. Elde edilen bu yansıma değerleri matematiksel formüllerle ifade edilen vejetasyon indisi değerlerine dönüştürülerek verim tahminlerinin belirlenmesinde kullanılabilir hale getirilmiştir. Elde edilen sonuçlar dikkate alındığında, Kenanbey çeşidi (15 Haziran 2019, Feekes 10.5.4) hariç, tüm ekmeklik çeşitler için özellikle erken çiçeklenme döneminde (25 Mayıs 2019, Feekes 10.5.1) hesaplanan spektral indekslerin verim tahmininde etkili olduğu belirlenmiştir. Tüm ekmeklik ve makarnalık çeşitlerde verimi tahmin etmek için belirlenen tüm indeksleri içeren ve çiçeklenme başlangıcı olan 25 Mayıs 2019 (Feekes 10.5.1) tarihli spektral bant bölgesinin etkili olduğu tespit edilmiştir. Tane verimi tahmininde erken çiçeklenme başlangıç döneminden (Feekes 10.5.1) başlayarak tane bağlama dönemi (Feekes 10.5.3) ve süt olum dönemine (Feekes 10.5.4) doğru spektral indekslerin korelasyon değerlerinde azalma olduğu tespit edilmiştir. Elde edilen bu indeks değerleri ile verim değerleri arasındaki korelasyonlar incelendiğinde öne çıkan fenolojik dönemler ve bu dönemlere ilişkin yüksek korelasyona sahip indekslerinin hesaplanabildiği belirlenmiştir. Günümüzde artık geleneksel hastalık takip yöntemlerinin yerine optik sensör teknolojisinin kullanımı ile verim tahmininde multispektral ve hiperspektral kameraların üzerinde yer aldığı insansız hava araçları ile alınan görüntülerin yapay zeka ve derin öğrenme teknikleri kullanılarak

yersel verilerle doğrulanması sonucu erken dönemde hızlı ve doğru bir şekilde verim tahminine yönelik yeni yaklaşımların geliştirilmesinin yolu açılmıştır.

Anahtar Kelimeler: Buğday, hiperspektral veri, sarı pas *(Puccinia striiformis* f. sp. *tritici*) hastalığı, spektral indeks, verim tahmini.

Introduction

Wheat which has been produced on earth for 8000 years and is one of the basic nutrients (carbohydrate, protein, vitamin, mineral, fibre source) of human beings (Curtis et al., 2022), is the third most produced crop in the world after corn and rice (Asseng et al., 2011). Wheat, corn and paddy are the three most produced grains in the world. Crop losses in crop production due to abiotic and biotic stresses (disease, pest and weed) cannot be predicted in advance according to the severity, intensity and duration of the stress in the plant, and overuse of chemicals used to control biotic stresses may cause irreversible environmental problems in the future and increase the resistance of stresses to chemicals (Li, et al., 1989). Diseases that cause yield and quality losses in plants can cause great economic losses in agricultural production. Therefore, observation and detection of plant diseases are of great importance for the sustainability of agricultural production (Strange and Scott, 2005).

Rust diseases caused by *Puccinia* species are the leading wheat diseases that cause significant yield and quality losses in wheat producing ecologies in the world (Roelfs, 1978; Samborski, 1985). Severe rust disease outbreaks are observed when one or more of some factors such as different rust species, climatic changes favourable for the development of the disease, cultural practices, cultivation of sensitive varieties and changing pathogen populations occur at the same time (Eversmeyer and Kramer, 2000). Yellow rust *(Puccinia striiformis* f. sp. *tritici)*, occurs all around and often results in epidemics in wet and cool springs in Turkey (Mert et al., 2012). Although the disease can also be seen on the leaves and spikes of the host, it can be easily identified by the yellow, light orange yellow colour, small and machine stitch-like summer spore structures, especially on the leaves. (Murray et al., 2005; Watkins, 2006). Yellow rust disease has a negative effect on the early development of the plant and can cause economic losses up to 70%. It is known that the yield decreases especially in sensitive varieties and has a negative effect on quality as the grain is smaller than it should be (Chen, 2005). It has been reported to cause severe yield and quality loss due to multiple epidemies of yellow rust in Turkey, especially during consecutive rains and low spring temperatures. It was reported that a loss of 1.5-2 million tons (50-60%) occurred only in the Southeastern Anatolia Region due to the yellow rust epidemic in 2010 (Aktaş et al., 2012).

According to reports, it was reported that the yellow rust disease epidemic caused a 26.5% crop loss in Gerek-79 bread wheat variety, which was cultivated more than 1 million tonnes in Central Anatolia cultivation areas (Braun et al., 1992). However, the severity of the disease depends on the resistance of the host, the time of first infection, the rate of disease development and the duration of the disease on the plant.

In recent years, methods developed with remote sensing techniques have made it possible to quickly and accurately reveal specific crop variables in the plant. With the help of spectral indices obtained as a result of the use of sensitive bands and their conversion into spectral reflectance values, it has become easy to predict different growth variables that directly affect the physiology and biochemistry of crops by eliminating the negative effects of the earth's surface. With the spectral reflectance values obtained from plants using "Remote Sensing" techniques, it is possible to obtain accurate and fast information about the characteristics of plant diseases and different phenological characteristics of vegetation (leaf, branch, spike, soil, etc.) (Zhang et al., 2011). Hyperspectral indices are used together with multispectral indices for accurate estimation of many vegetation parameters. Recent developments in optical sensor technology have shown that plant diseases can be detected directly from the leaf surface of plants under field conditions (Zhang et al., 2012b). Among different types of remote sensing techniques, hyperspectral remote sensing is one of the most effective methods in terms of capturing weak signals in the spectrum thanks to its high resolution (Goetz et al., 1985). Hyperspectral analyses can be widely used to monitor plant vigour and stress factors (Leaf Area Index, pigment coverage, plant diseases and pests, etc.) (Haboudane et al., 2004; Moshou et al., 2004; Oppelt and Mauser, 2004; Duveiller et al., 2011; Zhang et al., 2012a). Therefore, different vegetation indices (VI) have been developed to identify these based on research done in the previous period. These indices have been widely used to detect diseases such as winter wheat rust diseases (*Puccinia* spp.) and septoria leaf spot (*Septoria tritici)* at the canopy level (Zhang et al., 2012a; Liu. et al., 2020; Yu, et al., 2018). Gündoğdu and Bantchina, (2018) utilized NDVI data in monitoring the spatial distribution and plot-based development of wheat and investigated the statistical relationships between yield and NDVI. The spectral-optical behaviour of a leaf depends on its structure and the structure of the pigments present in it. Hyperspectral analysis can be widely used in the observation of different stress factors in plants. Recent developments in optical sensor technology have shown that plant diseases can be detected directly from the leaf surface of plants under field conditions (Zhang et al., 2012a). Models used in yield estimation studies (Plant growth models DSSAT-AQUACROP) will provide benefits for the purpose of obtaining reference information in advance for the early estimation of crop losses.

Different vegetation indices (VI) have been developed with recent research. These indices are widely used to determine winter wheat rusts and Septoria tritici blotch *(Septoria tritici)* at the canopy level (Zhang et al., 2012b; Yu et al., 2018; Liu et al., 2020). Canopy reflectance measurements are also made in 7-day periods from mid-May to the end of June. The obtained spectral values are evaluated with vegetation indices known in the literature. Rust diagnosis can be made by interpreting various indices obtained reading values obtained from healthy and diseased plants using different sensors. Wideband vegetation indices, which are widely used in the diagnosis of plant diseases to distinguish between normal and abnormal plants, include band regions developed according to plant stress factors (Delwiche and Kim, 2000). It has been reported that the reflectance values used in the detection of yellow rust in winter wheat are in the band ranges of 680, 725 and 750 nm (Yang et al., 2005).

The aim of this research is to determine the effective hyperspectral reflection characteristics in determining the yield losses that yellow rust may cause in some winter bread and durum wheat varieties under artificial epidemic conditions "in the range of 331-1141 nm of the spectral region" at different growth stages. Study result;

It is to determine the spectral band regions and indices that are effective in determining the phenological periods and grain losses that may be important in determining the yield losses caused by yellow rust in different growth stages of wheat.

It was observed that optical sensor technology used in yield estimation on different wheat varieties was effective in revealing important periods and spectral band ranges in yield estimation according to phenological periods. For this purpose, the changes in spectral reflectance values due to morphological changes of plants under different disease dose applications were converted into index values and correlated with yield values. As a result, it was possible to predict the changes in yield depending on the severity of the disease in a fast and accurate way. In the face of the difficulty of predicting the results of the disease evaluations made by traditional methods, these data obtained by optical methods have revealed faster and more accurate approaches in yield estimation.

Material and Method

Climatic and Soil Characters of the Research Area

The research was conducted in Yenimahalle/Ankara/Turkey during the 2018–2019 growing season at the Field Crops Central Research Institute (CRIFC) Yenimahalle (Ankara) campus. The monthly average climate data (Anonymous, 2022) for the Yenimahalle location are given in Table 1. In this period, the average monthly precipitation was 33.2 mm. and the temperature was 12.08°C. The texture of the soil in the research area was determined to be clay loam.

Table 1. Monthly average climate data for Yenimahalle location (2018-2019)

Climate Data	Month (2018 Year)					Month (2019 Year)							
	XIII	IX	X	XI	XII	I	II	III	IV	V	VI	VII	Mean
Average Temperature (°C)	25.0	20.0	14.94	9.0	3.3	2.0	4.8	7.2	10.8	18.2	22.4	23.1	12.08
Highest Temperature, (°C)	32.0	33.2	21.65	23.5	12.6	10.8	15.8	20.4	25.5	34.2	33.4	34.9	24.43
Lowest Temperature, (°C)	18.0	8.1	9.43	-2.3	-10.2	-10.4	-2.4	-3.3	-0.9	6.1	11.7	10.7	0.71
Precipitation, (mm)	10.0	7.4	1.57	24.9	60.4	40.6	33.2	38.0	28.9	30.8	37.4	30.4	33.2
Relative humidity , (%)	37.0	46	69.83	65	81	79	70.2	55.4	42.5	47.2	52.1	42.0	58.04
Wind speed , m/s^{-1} (2 m.)	2.0	2.1	2.2	1.6	1.5	1.7	2.0	2.1	1.3	1.3	1.6	1.8	1.7

Plant Materials

In the research, four winter bread wheat and four winter durum wheat varieties were used to research the seasonal effects of yellow rust with hyperspectral data (multi-band). The yellow rust reactions of all test materials are given in Table 2. On the other hand Little Club genotype was used as susceptible control test material.

Table 2. Bread and durum varieties used in research, registration years, yellow rust reactions

Bread Group			Durum Group		
Variety	**Registration Year**	**Disease Reaction**	**Variety**	**Registration Year**	**Disease Reaction**
Bayraktar 2000	28.04.2000	Moderate Susceptible	Çeşit-1252	26.04.2000	Moderate Susceptible
Demir 2000	28.04.2000	Susceptible	Eminbey	06.04.2009	Resistant
Eser	02.05.2003	Resistant	Kızıltan 91	26.04.1991	Moderate Susceptible
Kenanbey	06.04.2009	Susceptible	Mirzabey	28.04.2000	Moderate Susceptible

Research design

The research material, four bread (Bayraktar 2000, Demir 2000, Eser and Kenanbey) and for durum (Çeşit-1252, Eminbey, Kızıltan 91 and Mirzabey 2000) wheat varieties, was planted in a randomized block design with three replications for four different yellow rust spore doses (0%, 25%, 50%, and 100%). The research consisted of 8 blocks, 2 blocks with no disease inoculation (negative control or 0% dose) and six blocks with disease inoculation at 25%, 50%, 100% disease administration doses. Each block was cultivated in three replications. Each variety was sown by hand in 3 rows, each 1 meter long, with 33-35 cm row spacing. The distance between replications was determined to be 50 cm to prevent disease transmission during inoculation. Among spore applications, the Little Club (LC) variety is grown both to control disease progression and to ensure the spread of disease in the field.

Disease inoculation and disease reaction determination

Yellow rust (*Puccinia striiformis* f. sp. *tritici*) spores' inoculation was homogenized in mineral oil (Soltrol 170®) at different application spore doses of yellow rust and 0% (negative control group), 25%, 50% and 100% doses (3, 6, and 12 mg/200 mL spore solution) were applied on the test material ULV.

The first inoculation was made on May 6, 2019 (Feekes 6 stage) and the second inoculation was made seven days after the first inoculation. Newly collected yellow rust spores are used for all spore doses of inoculation and the aim is to obtain the most viable spores in this way. Inoculation is mainly performed in windless, cool weather conditions, and plastic barriers are used between plots to prevent the spore dose applied for dose applications from passing to the other plant material areas.

Yellow rust reaction evaluations were determined using the "Modified Cobb" scale, together with the severity of yellow rust (Peterson et al., 1948) and the reaction types of plants against yellow rust (Roelfs et al., 1992). The first evaluation was started when the susceptible control Little Club genotype reached the level of 80S, and the disease reaction was observed as 100S in the second evaluation. As a result of this evaluation of the susceptible control genotype, it was interpreted that the results of the reaction tests were reliable and that all the material was evaluated. After all reaction evaluations, the Infection Coefficient (EC) was calculated. Rust severity and the type of infection were recorded in the evaluations. In the evaluations made according to the Infection Coefficient, five groups made by Akan (2019) were used.

Hyperspectral data collection and data analysis *(Spectral Reflection Measurements)*

Hyperspectral data were collected in different phenological development periods (Feekes) for all test material (Large, 1954). Observations were made in 3 periods, on May 25 2019 (Flowering Beginning (Early Period) period (Feekes 10.5.1), June 15 2019 (Grain Binding (Early-Middle Period) period (Feekes 10.5.3), and June 23 2019 (Milk Settlement (Middle-Late Period) period (Feekes 10.5.4), when disease reactions were evaluated. Spectroradiometric canopy reflectance measurements were made using a portable handheld spectroradiometer device between 11:00 and 15:00, when the sun's rays were perpendicular to the earth. Spectral reflectance measurements (once a week) were made using a spectral sensor at 3 nm intervals with a bandwidth of 330-1150 nm at different growth stages (between flowering and milk period) of wheat. Measurements were made from a height of 25 cm from the plant canopy surface at an angle of 25° to the soil surface. The measurements made using the spectral sensor were transferred to the computer environment simultaneously using the cable connection.

The spectroradiometer used in the measurements is single-channel and includes UV/VIS/NIR band channels, and a total of 256 evaluations were made, with each channel every 3 nm in the range of 331-1141 nm. Electronic length of measurements made; 16 bits (actually 14.5 bits) and wavelength resolution 4-7 nm, integration time 5 ms when light is sufficient. Prior to spectral reflectance measurements, the spectroradiometer was calibrated using a standard white plate (Ba_2SO_4). With the calibration, it has been possible to minimize the negative effects caused by noise and atmosphere.

Calculation of vegetation indices and statistical analysis

Vegetation indices calculated by using reflectance values over the 331-1141 nm band gap of the electromagnetic spectrum for the diagnosis of yellow rust, together with their literature (27 literature) are given in Table 3. The correlation relationship between the disease severity (DI%) values calculated from the disease readings made in different phenological periods and the index values was evaluated. These correlation values were used to develop regression models for disease reaction prediction.

To test the performance of the resulting yellow rust prediction regression model, the correlation differences (R^2) between the disease reactions observed (in the classical visual disease assessment on the plant) and the predicted disease assessments obtained from the model were calculated. In addition to this calculation, mean error sum of squares (RMSE) and standard error (SE%) values were calculated separately for each index. When the results were evaluated together; It was determined that the indices with a larger R^2 value and smaller RMSE and %SE values yielded effective results in determining the disease severity (DI%) in the plant. The linear regression equations for estimating disease severity could be obtained by cross-validation between the estimated disease severity values and the observed actual disease severity values.

For all phenological periods, regression and correlation analyses were performed using the SPSS® statistical program (SPSS-22® version), and basic statistical and variance analyzes were performed. (IBM Corp., 2014). The error sum of squares (RMSE) and relative error percentage (SE%) were calculated using the following equations (Liu et al., 2020).

$$\text{Error sum of squares (RMSE)} = \sqrt{1/n \sum_{i=1}^{n} (\bar{y}_i - \hat{y}_i)^2} \quad \textbf{(1)}$$

$$\text{Relative error percentage (RE \%)} = \frac{\text{Error sum of squares (RMSE)}}{\bar{y}_i} * 100 \quad \textbf{(2)}$$

In the formula:

yi *= Calculated index value*

$\hat{y}_i$ *= Calculated value from the correlation equation*

$\bar{y}_i$ *= Average dsease severity value (DL%)*

n *= Number of Samples used in the experiment*

Table 3. Vegetation indices used in the distinction of diseased and disease-free plants

Vegetation İndices	Description	Formula	Area of Influence	References
NDVI	Normalized Difference Vegetation Index	$(R_{830} - R_{675})/(R_{830} + R_{675})$	Leaf Area Index, Photosynthetically Active Radiation (PAR), or Biomass (PAB)	Rouse et al., 1974
NBNDVI	Narrow-Band Normalized Difference Vegetation Index	$(R850 - R680)/(R850 + R680)$	Used to Follow Vegetation	Thenkabail et al., 2000
NRI	Nitrogen Reflectance Index	$(R570 - R670)/(R570 + R670)$	Nitrogen Status	Filella et al., 1995
PRI	Photochemical Reflectance Index	$(R570 - R531)/(R570 + R531)$	Photosynthetic Radiation (PR)	Gamon et al., 1992, Huang et al., 2014
TCARI	The Transformed Chlorophyll Absorption and Reflectance Index	$3 \times [(R_{700} - R675) - 0.2 \times (R700 - R550) \times (R700/R670)]$	Chlorophyll a + b Concentration	Haboudane et al., 2002

SIPI	Structural Independent Pigment Index	(R800 − *R*445)/ (*R*800 − *R*680)	Pigment Concentrations	Peñuelas et al., 1995, Devadas et al., 2009
PhRI	Physiological Reflectance Index	(R550 − R531)/ (*R*550 + *R*531)	Calculating Light Usage Efficiency	Gitelson et al., 2001
NPCI	Normalized Pigment Chlorophyll Ratio Index	(R680 − *R*430)/ (*R*680 + *R*430)	Pigment Concentrations	Kim et al., 1994
ARI	Anthocyanin Reflectance Index	$ARI = (R550)^{-1} - (R700)^{-1}$	Anthocyanin Content	Zarco-Tejada et al., 2005
CARI	Chlorophyll Absorption Ratio Index	(|(*a*670 + *R*670 + *b*)|/(*a*2 + 1)1/2) × (*R*700/*R*670) *a* = (*R*700 − *R*550)/150, *b* = *R*550 − (*a* × 550)	Calculating Chlorophyll Absorption	Zarco-Tejada et al., 2005
GI	Green Index	*R554/R677*	Pigment Concentrations	Broge and Leblanc, 2001
TVI	Triangular Vegetation Index	0.5[120(R750 − *R*550) − 200(*R*670 − *R*550)	Determination of plant status	Haboudane et al., 2004
MCARI	Modified Chlorophyll Absorption İn Reflectance Index	(R701 − R671) − 0.2(R701 − R549)]/(R701/R671)	Calculating Chlorophyll Absorption	Daughtry et al., 2000
PSRI	Plant Senescence Reflectance Index	(R680 − R500)/R750	Pigment Coverage, Leaf Maturation and Yellowing	Merzlyak et al., 1999
RVSI	Red-Edge Vegetation Stress Index	*RVSI= [(R712 + R752)/2] − R732*	Internal Structure Parameters	Merton and Huntington, 1999
WI	Water Index	WI= R900/R970	Calculation of Changes in Water Amount	Peñuelas et al., 1997
LCCI	Leaf and Canopy Chlorophyll Index)	$LCCI = (R_{750} - R_{705}) / (R_{750} + R_{705})$	Calculating Chlorophyll Absorption	Gitelson and Merzlyak 1994
NVI	New Vegetation Index	$NVI = (R_{777} - R_{747}) / (R_{673})$	Calculating Chlorophyll Absorption	Gupta, et al., 2001
GNDVI	Green Normalized Difference Vegetation Index	$GNDVI = (R_{750} - R_{550}) / (R_{750} + R_{550})$	Leaf Area Index, Photosynthetically Active Radiation (PAR), or Biomass (PAB)	Gitelson et al., 1996
SRPI	Simple Ratio Pigment Index	$SRPI = R_{430} / R_{680}$	Pigment Concentrations	Peñuelas et al., 1994
RVI	Ratio Vegetation Index	$RVI = R_{NIR}/R_{Red}$	Biophysical Changes and Disease Tracking	Jordan 1969
RDVI	Renormalized Difference Vegetation Index	$RDVI = (R_{800} - R_{670}) / (R_{800} + R_{670})^{0,5}$	Relationships Between Biophysical Parameters	Roujean and Breon, 1995
DVI	Difference Vegetation Index	$DVI = R_{890} - R_{670}$	Investigation of Changes in Vegetation	Jordan 1969
NLI	Non-Linear Vegetation Index	$NLI = (R^2_{NIR} / R_R) / (R^2_{NIR} + R_R)$	Leaf Area Index Calculation	Goel and Qin 1994
SR	Simple Ratio	$SR = R_{NIR} / R_R$	Monitoring Vegetation	Baret and Guyot 1991
MSR	Modified Simple Ratio Index	$MSR = (R_{800}/R_{670} - 1)/sqrt(R_{800}/R_{670} + 1)$	Leaf Area Index Calculation	Chen and Cihlar1996
YRI	Yellow Rust Index	$YRI = (R_{730} - R_{419}) / (R_{730} + R_{419}) + 0.5R_{736}$	Wheat Diseases	Huang et al., 2014

Results

Yield-index relationships under disease reactions practices

Yield-index relationships determined in disease applications in bread varieties

“Descriptive Analysis” (IBM SPSS Version 22.0) was carried out in order to determine the changes in yield calculated from the unit area of different yellow rust spore dose applications in bread varieties affected by yellow rust spore doses. As a result of the evaluations, the highest yield was determined in the Bayraktar 2000 variety (4274.75 kg/ha), followed by the Demir 2000 variety (2746.80 kg/ha) (Table 4). Yields close to each other were determined in the Eser (1856.75 kg/ha) and Kenanbey (1848.68 kg/ha) varieties. For Bayraktar 2000, the relationships between the mean grain yield (kg/ha) of replication in different phenological periods and the spectral indices were investigated. The highest “Pearson Correlation” values are SRPI (680-430), (R^2= 0.918), GI (554-677), (R^2= 0.899), NRI (670-570) (R^2= 0.893), PSRI (750-500)) (R^2= 0.891), ARI (700-550), (R^2=-0.934), NPCI (680-430) (R^2=-0.923), PhRI (550-531), (R^2=-0.920), PRI (570-531) (R^2=-0.916) was determined in the early period when the spectral band region was effective on May 25, 2019 (Feekes 10.5.1), which is the flowering beginning in which the indices are included (Table 5). In the estimation of the grain yield of Bayraktar 2000 variety, a decrease in the correlation values of the spectral indices was detected starting from the flowering beginning period (Feekes 10.5.1) to the grain binding period (Feekes 10.5.3) and milk settlement period (Feekes 10.5.4) periods. Average yield values obtained from replications of bread varieties according to disease application doses are shown in Table 4.

Table 4. Yellow rust spore dose-average yield relationships in bread wheat varieties according to the average replication rates (Descriptive Analysis).

Variety	Calculated Yield Per Unit Area (kg /ha)		
	Replication	Mean (kg/ ha)	Standard Deviation
Bayraktar 2000	12	4274.75	1152.08
Demir 2000	12	2746.80	1004.17
Eser	12	1856.75	434.73
Kenanbey	12	1848.68	206.71

For the **Bayraktar**, when the relationships between the mean recurring grain yield (kg/ha) and spectral indexes were examined in different phenological periods, the highest Pearson correlation values were found in the flowering beginning (early period) (Feekes10.5.1) ARI, NPCI, PhRI, SIPI, SRPI, PRI, GI, NRI, PSRI, GNDVI, YRI, NDVI indices were in the correlation range R^2= 0.537-0.933, for the Demir 2000, RDVI, PRI, DVI PhRI, SIPI, GI, PSRI, SRPI, TVI, GNDVI, MCARI indices were in the range of R^2= 0.528-0.763 in the early period, for the **Eser**, RVSI, PRI, PhRI, PSRI, GI, SIPI, RI, DVI. , NRI, NPCI, ARI, SRP, MCARI indices were found in the correlation range R^2= 0.665-0.747 in the early period, for **Kenanbey**, high correlation values were determined in the middle-late period (15 June 2019, 10.5.4) with the indices of YRI, CARI, NLI, RVI, SR, ARI, NBNDVI, WI, SIPI, NPCI, GNDVI, and the correlation range of R^2= 0.400-0.805.

The spectral band region dated May 25, 2019 (Feekes 10.5.1), which is the flowering beginning and includes all indices, was found to be effective for the estimation of yield in bread varieties. In the estimation of grain yield, it was determined that there was a decrease in the correlation values of the spectral indices starting from the flowering beginning period (Feekes 10.5.1) towards the grain binding period (Feekes 10.5.3) and milk settlement period (Feekes 10.5.4) periods (Table 5) (Figure 1).

Table 5. According to phenological development periods relationships between grain yield and spectral indexes for bread varieties.

	Phenological Period	Indices	Correlation Range (Pearson-R^2)
Demir 2000	**10.5.1**	**RDVI, PRI, DVI, PhRI, SIPI, GI, PSRI, SRPI, TVI, GNDVI, MCARI**	**0.528-0.763**
	10.5.3	PhRI, SRPI, NPCI, GNDVI, ARI, NBNDVI, PRI, PSRI	0.353-0.589
	10.5.4	SR, RVI, NLI, YRI, NPCI, SRPI, CARI	0.317-0.557
Kenanbey	**10.5.1**	SR, RVI, WI, NRI, GI, CARI, GNDVI	0.208-0.396
	10.5.3	PSRI, NPCI, SRPI, SIPI, LCCI, NRI, GI, MSR, PRI, NVI, RDVI, NDVI	0.368-0.592
	10.5.4	**YRI, CARI, NLI, RVI, SR, ARI, NBNDVI, WI, SIPI, NPCI, GNDVI**	**0.400-0.805**
Bayraktar 2000	**10.5.1**	**ARI, NPCI, PhRI, SIPI, SRPI, PRI, GI, NRI, PSRI, GNDVI, YRI, NDVI**	**0.537-0.933**
	10.5.3	PhRI, SRPI, NPCI, NVI, NBNDVI, GNDVI, PRI, MSR, CARI, NDVI	0.312-0.598
	10.5.4	YRI, NLI, WI, ARI, CARI, GNDVI, SR, RVI, GI, NRI, PhRI, PRI, NDVI	0.343-0.629
Eser	**10.5.1**	**RVSI, PRI, PhRI, PSRI, GI, SIPI, RI, DVI, NRI, NPCI, ARI, SRP, MCARI**	**0.665-0.747**
	10.5.3	GNDVI, PhRI, NBNDVI, NVI, MSR, NDVI, ARI, DVI, LCCI, CARI	0.321-0.552
	10.5.4	NLI, MCARI, TCARI, YRI, SR, NRI, DVI, GI, TVI, RDVI, PhRI	0.250-0.452

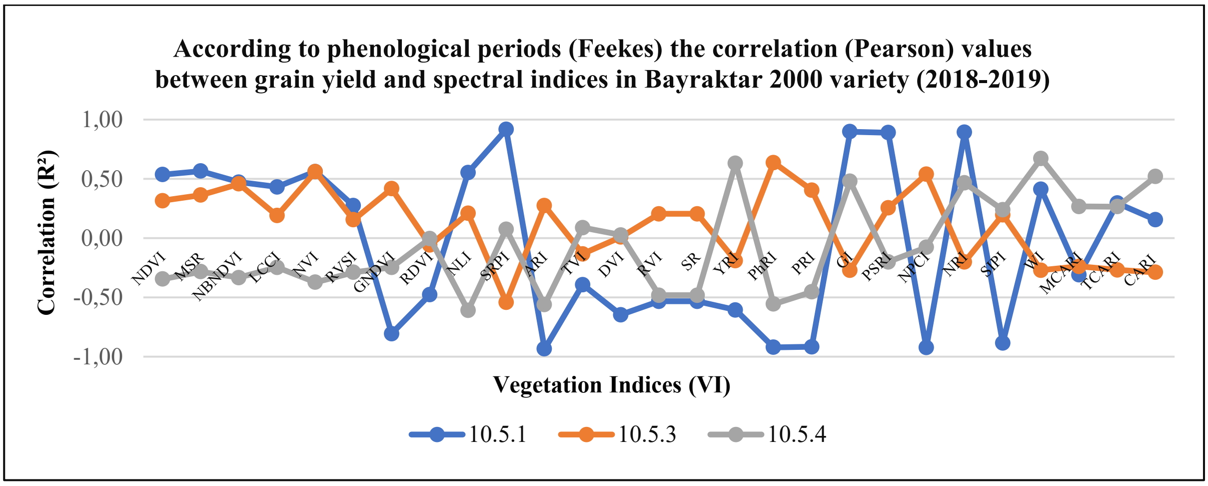

Figure 1. *Correlation values between grain yield-spectral indexes according to phenological periods in Bayraktar 2000.*

When the average yields of bread varieties were evaluated together, Bayraktar 2000 was determined to be the variety that was least affected by different yellow rust spore doses (0%, 25%, 50%, 100%) with all test material without disease (negative control group). With increasing yellow rust spore doses, an increase in disease severity was determined however, high yield values were determined in the Bayraktar 2000 (4274.75 kg/ha) variety.

The least affected resistant variety in terms of yield despite the different doses of disease treatments (25%, 50%, 100%) was Bayraktar (4274.75 kg/ha), followed by Demir 2000 (2746.80 kg/ha), and the most affected varieties were Kenanbey (1848.68 kg/ha) and Eser (1856.75 kg/ha), respectively. The most effective phenological period for yield estimation in bread varieties was early (10.5.1) except Kenanbey, while the period directly related to yield was found to be mid-late (10.5.4) in Kenanbey variety.

Yield-index relationships determined in disease applications in durum varieties

The changes in the average yield calculated from the unit area as a result of the reactions of durum wheat varieties to different disease application doses were examined with the results of "Descriptive Analysis". As a result, it was determined that the variety with the highest yield was Eminbey (2935.05 kg/ha), followed by Cesit-1252 (2526.30 kg/ha), Kızıltan 91 (2499.76 kg/ha) and Mirzabey 2000 (1738.98 kg/ha) (Table 6).

Table 6. According to recurrence averages disease dose-average yield relationships in durum wheat varieties (Descriptive Analysis).

Variety	Calculated Yield per Unit Area (kg/ha)		
	Recurrence	**Mean**	**Standard deviation**
Kızıltan 91	12	2499.76	113.814
Çeşit-1252	12	2526.30	68.299
Eminbey	12	2935.05	92.442
Mirzabey 2000	12	1738.98	74.668

In terms of yield of durum varieties, the least affected variety was Eminbey (2935.05 kg/da), followed by Çeşit 1252 -1252 (2526 kg/da) and the most affected varieties were Mirzabey 2000 (1738 kg/da) and Kiziltan-91 (2499.76 kg/da). The period directly related to yield was found to be early (10.5.1) in all of the varieties.

In order to test the reactions of durum wheat varieties to different yellow rust spore doses and to estimate yield averages, unit area, replication yield averages and spectral reflection values for different phenological periods of durum wheat varieties were calculated. Correlations with average yield values and vegetation indices were examined, and prominent phenological periods and high correlation indexes for these periods were calculated. Considering the results obtained, it was evaluated that the spectral indices calculated especially in the flowering beginning (Early period, Feekes 10.5.1) for all durum wheat varieties were effective in yield estimation (Table 7).

When the relations between the mean recurring grain yield (kg/ha) values and spectral indexes for the Kızıltan 91 according to different phenological periods were examined, the highest Pearson Correlation values were found in the flowering beginning (Early period, Feekes10.5.1) to be PRI, ARI, CARI, NPCI, PhRI, NDVI, NRI GI, SRPI, MSR indices (R^2= 0.813-0.857), for the Çeşit-1252 according to different phenological periods were examined, the highest Pearson Correlation values were found in the flowering beginning (Early period, Feekes10.5.1) to be PRI, NRI, PhRI, ARI, GI, RVSI, PSRI, SIPI, NPCI, SRPI indices (R^2= 0.885-0.892), for Kızıltan-91 high correlation was determined in the correlation range of PRI, ARI, CARI, NPCI, PhRI, NDVI, NRI, GI, SRPI, MSR indices (R^2= 0.813-0.857), for Mirzabey 2000 high correlation was determined in the correlation range of GI, SRPI, PSRI, NPCI, NRI, SIPI, PRI, ARI, GNDVI indices (R^2= 0.702-0.936), for Eminbey, high correlation was determined in the correlation range of WI, LCCI, NVI, NDVI, MSR, RDVI, NBNDVI, TVI indices (R^2= 0.216-0.533).

The spectral band region of May 25, 2019 (Feekes 10.5.1), which is the beginning of flowering, and includes all indices that can be used in yield estimation in durum varieties, was evaluated as effective. In the estimation of grain yield, a decrease in the correlation values of spectral indices was determined starting from the flowering beginning period (Feekes 10.5.1) towards the grain binding period (10.5.3) and milk settlement period (10.5.4) periods (Figure 2).

Table 7. According to different phenological development periods the relationships between grain yield-spectral indices for durum varieties.

	Phenological Period	Indices	Correlation Range (Pearson-R^2)
Kızıltan 91	**10.5.1**	**PRI, ARI, CARI, NPCI, PhRI, NDVI, NRI, GI, SRPI, MSR**	**0.813-0.857**
	10.5.3	PhRI, RVSI, RDVI, DVI, NDVI, TVI, NVI, LCCI, GNDVI	0.328-0.622
	10.5.4	NDVI, NBNDVI, SIPI, NVI, DVI, GNDVI, MSR,	0.327-0.417
Çeşit-1252	**10.5.1**	**PRI, NRI, PhRI, ARI, GI, RVSI, PSRI, SIPI, NPCI, SRPI**	**0.885-0.982**
	10.5.3	GNDVI, NDVI, NBNDVI, MSRNVI, LCCI, SIPI, ARI, PhRI, CARI	0.339-0.559
	10.5.4	WI, TCARI, TVI, DVI, GI, MCARI	0.270-0.415
Eminbey	**10.5.1**	**WI, LCCI, NVI, NDVI, MSR, RDVI, NBNDVI, TVI**	**0.216-0.533**
	10.5.3	WI, ARI, MCARI, CARI, YRI, NBNDVI, NVI, GNDVI	0.208-0.481
	10.5.4	SR, YRI, CARI, WI, PhRI, TCARI, GI, ARI, TVI, NLI, MCARI	0.287-0.508
Mirzabey 2000	**10.5.1**	**GI, SRPI, PSRI, NPCI, NRI, SIPI, PRI, ARI, GNDVI**	**0.702-0.936**
	10.5.3	CARI, PhRI, ARI, NBNDVI, NLI, GNDVI, MCARI, MSR, WI, RVI	0.316-0.656
	10.5.4	YRI, CARI, NLI, ARI, NBNDVI, WI, NDVI, SIPI, PhRI, MSR, PRI	0.432-0.768

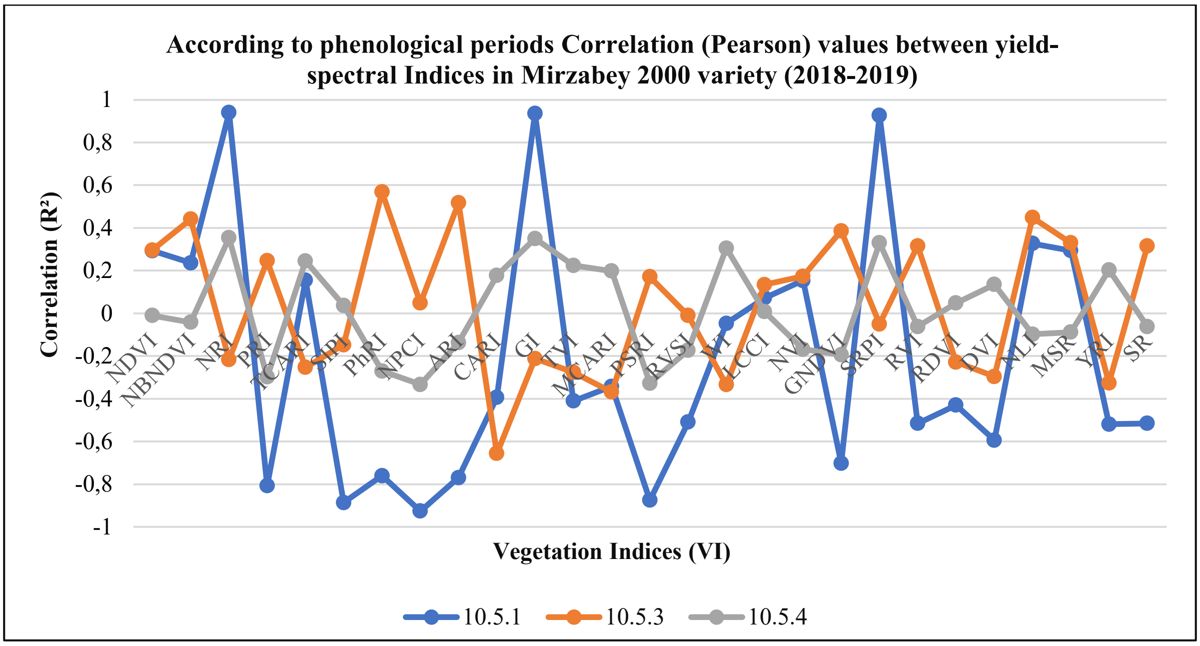

Figure 2. *According to phenological periods correlation values between grain yield-spectral indices in Mirzabey 2000*

Discussion

Evaluation of changes in yield depending on disease severity;

Vegetation indices were used to identify plants affected by the disease in different phenological periods. These vegetation indices are important in determining the plant affected by the disease, showing strong correlations with the yield averages calculated from the unit area. Previous research indicates that a number of studies have recently used remote sensing indices for crop monitoring and crop production forecasts, including the Enhanced Vegetation Index (EVI), Green Normalized Difference Vegetation Index (GNDVI), and Weighted Difference Vegetation Index (WDVI) (Naqvi et al., 2019). Using a linear regressive link between the spatial accumulation of NDVI and the output of winter wheat, Prasad et al., (2006) used MODIS-NDVI data to estimate regional yield production in China. According to Sultana et al., (2014), grain yield and NDVI at maturity have a greater association than NDVI values observed at other growth stages.

In a study conducted by Vergara-Diaz, et al., 2015 between 2010 and 2013, the most effective method against yellow rust was to increase the number of grains and for this purpose, the canopy was analyzed using vegetation indices (Red, Green, and Blue) under field conditions and yield, disease severity were estimated for this purpose, the NDVI vegetation index was used, resulting in high correlation values (R^2 = 0.581 and R^2 = 0.536). Grain yield losses in the presence of yellow rust were higher in late-eared varieties. The relationship between RGB-based indices and the number of days to head of the varieties explained 70.9% of the variability in grain yield and 62.7% of the yield losses. Significant genotype differences were found during tillering and stemming using the NDVI index. RGB indices are a good indicator of yield estimation when yellow rust is present in the field. Some researchers have reported that NDVI values obtained from satellite-based systems for estimating yield in barley yield more successful results (Kumhlov and Matjkov 2017). Kumhlov and Matikov, 2017 compared the images obtained from QuickBird and WorldView-2 satellites and the NDVI values obtained from the GreenSeeker device in their study, where they examined the possibilities of using remote sensing methods in yield estimation on winter barley. When the obtained NDVI values and efficiency are compared, it has been reported that the data obtained from satellite-based systems is more successful than the estimation of efficiency from GreenSeeker data. Fabbri et.al., (2020) reported that in their studies on barley, they found a highly significant positive correlation between the NDVI and yield values taken during the growing period from the tillering period to the milk production period.

When the relations between the mean replication grain yield (kg/ha) values and spectral indexes in bread varieties;

In this study considering the results obtained, it was determined that spectral indices calculated especially in the flowering beginning period (May 25, Feekes 10.5.1) for all bread varieties, excluding the Kenanbey variety (15 June, Feekes 10.5.4), were effective in yield estimation. When the correlations between the replication yield averages and the spectral indices were examined in Eser variety, high correlation values were observed in the RVSI, PRI, PhRI, PSRI, GI, SIPI, RI, DVI, NRI, NPCI, ARI, SRP, MCARI indices during the flowering beginning (Feekes 10.5.1) period. (R^2= 0.813-0.857). In the estimation of the grain yield of Bayraktar 2000 variety, a decrease in the correlation values of the spectral indices was detected starting from the flowering beginning period (Feekes 10.5.1) to the grain binding period (Feekes 10.5.3) and milk settlement period (Feekes 10.5.4) periods. Bayraktar 2000 variety showed high correlation in ARI, NPCI, PhRI, SIPI, SRPI, PRI, GI, NRI, PSRI, GNDVI, YRI, NDVI indices (R^2= 0.537-0.933). Demir 2000 variety showed high correlation in RDVI, PRI, DVI PhRI, SIPI, GI, PSRI, SRPI, TVI, GNDVI, MCARI indices in the early period. (R^2= 0.528-0.763). Kenanbey variety showed high correlation values in YRI, CARI, NLI, RVI, SR, ARI, NBNDVI, WI, SIPI, NPCI, GNDVI indices during the milk settlement period (Feekes 10.5.4) (R^2= 0.400-0.805). Indices, which generally include the flowering onset period (May 25, Feekes 10.5.1), were found to be effective in predicting yields for bread wheat varieties. In the early period, RI, DVI, SIPI and PhRI for Eser, Bayraktar 2000 and Demir varieties showed high correlations, whereas YRI, NLI, CARI, RVI and SR indices were highly correlated in the late rotation (Feekes 10.5.4). In yield estimation, a decrease was observed in correlation values from the flowering beginning period (10.5.1) to the milk settlement period (10.5.4). On the other hand, the late yellowing period was found to be effective in the yield estimation of the Kenanbey variety.

When the relations between the mean replication grain yield (kg/ha) values and spectral indexes in durum varieties;

All durum wheat varieties showed high correlation in the early period (Feekes 10.5.1) in yield estimation. For the **Kızıltan 91** variety, according to different phenological periods determined, the highest "Pearson Correlation" values were found in the flowering beginning period (Feekes 10.5.1) to be PRI, ARI, CARI, NPCI, PhRI, NDVI, NRI GI, SRPI, MSR indices (R^2= 0.813-0.857). For the **Çeşit-1252** variety high correlation was determined in the correlation range of PRI, NRI, PhRI, ARI, GI, RVSI, PSRI, SIPI, NPCI, SRPI indices (R^2=

0.885-0.982). For the **Eminbey** variety, high correlation was determined in the correlation range of WI, LCCI, NVI, NDVI, MSR, RDVI, NBNDVI, TVI indices (R^2= 0.216-0.533). For the **Mirzabey 2000** variety**,** high correlation was determined in the correlation range of GI, SRPI, PSRI, NPCI, NRI, SIPI, PRI, ARI, GNDVI indices (R^2= 0.702-0.936). In the early period, PRI, ARI, NRI, NPCI, PhRI, GI and SRPI indices for Kızıltan 91, Bayraktar 2000 and Demir varieties, and WI, LCCI, NVI, NDVI and MSR indices for Eminbey varieties showed high correlations.

The spectral band region of May 25, 2019, which is the flowering beginning period (Feekes 10.5.1), which includes all indices that can be used in yield estimation in durum varieties, was evaluated as effective. In the estimation of grain yield, a decrease in the correlation values of spectral indices was determined starting from the flowering beginning period (Feekes 10.5.1) towards the grain binding period (Feekes 10.5.3) and milk settlement period (Feekes 10.5.4) periods.

In the evaluation according to yellow rust spore doses applications;

For bread varieties: It has been determined that the early period (May 25, 2019, 10.5.1) is effective in yield estimation. It was determined that the spectral indices calculated especially in the early period (May 25, 2019, 10.5.1) for all bread varieties except Kenanbey (June 15, 2019, 10.5.4) were effective in yield estimation. It was determined that the Bayraktar 2000 variety was the least affected by disease severity in terms of yield characteristics, and the highest unit area yield was determined in this variety.When all phenological periods were evaluated together in the Kenanbey and Demir 2000 varieties, although significant increases in disease severity, were detected no significant change in yield could be determined. When all phenological periods were evaluated together in the Kenanbey and Demir 2000 varieties, although significant increases in disease severity were detected, no significant change in yield could be determined. In general, Average yields increased due to increasing yellow rust severity. It was interpreted that the Bayraktar 2000 variety was less affected, the Demir 2000 and Kenanbey varieties were moderately affected, but the Eser varieties were more affected.

For durum varieties; According to the phenological periods used in the estimation of the yield of durum wheat varieties, their reactions to the disease were tested with the index values obtained from the reflection values at different application doses (25%, 50%, and 100%) As a result, it was determined that the correlation values obtained in the early period (May 25, 2019, 10.5.1) were high and effective in yield estimation. In the evaluation made in terms of yield characteristics, it was determined that Mirzabey 2000 and Çeşit-1252 were the least affected varieties when compared to plants without disease. Limited yield increases were observed in disease-treated varieties compared .

For plants that do not show disease. This situation was interpreted as indicating that Mirzabey 2000 and Çeşit-1252 varieties were tolerant to the disease. It was determined that Eminbey was affected by disease treatments at a limited level. In an evaluation of the average yield, it was determined that Kızıltan 91 was the most affected (susceptible) durum wheat variety to yellow rust.

Conclusion

To see how different doses of yellow rust spores affect different types of bread wheat and to get an idea of the average yield, the replication yield averages were calculated from the unit area of the bread varieties and the spectral reflectance values for different stages of growth. These reflectance values were turned into index values, and the correlations between these index values and yield values were looked at. As a result, prominent phenological periods and indices with high correlations for these periods were calculated. Considering the results obtained, it was determined that spectral indices calculated especially in the early period (May 25, 2019, 10.5.1) for all bread varieties, excluding Kenanbey (June 15, 2019, 10.5.4), were effective in yield estimation.

Spectral reflection values were calculated for different phenological periods and their correlations with vegetation indices were examined prominent phenological periods and high correlation indices related to these periods were calculated. Considering the results obtained, it was determined that the spectral indices calculated especially in the flowering beginning period (May 25, 2019, Feekes 10.5.1) for all bread varieties, excluding the Kenanbey variety (June 15, 2019, Feekes 10.5.4) are effective in yield estimation. It was determined that the spectral band region of May 25, 2019 (Feekes 10.5.1), which is the beginning of flowering was effective which includes all indices determined to predict yield in all bread and durum varieties. In the estimation of grain yield, it was determined that there was a decrease in the correlation values of the spectral indices starting from the flowering beginning period (Feekes 10.5.1) towards the grain binding period (Feekes 10.5.3) and milk settlement period (Feekes 10.5.4). High correlation values were found in the early period (Feekes 10.5.1) in the estimation of yield in bread varieties in the ARI, NPCI, PhRI, SIPI, SRPI, PRI, GI, NRI, PSRI, GNDVI,YRI and NDVI indices of Bayraktar 2000 variety (R^2= 0.400-0.805). Among the durum varieties, the highest correlation values were found in the PRI, NRI, PhRI, ARI, GI, RVSI, PSRI, SIPI, NPCI and SRPI indices of the Çeşit-1252 variety (R^2= 0.885-0.982).

The wide range of genotypic differences present in most RGB indices at all growth stages is instrumental in revealing yield variability. The NDVI has been used with satisfactory results in many predictions in field-level yield models for wheat (Aparico et al., 2000). In fact, regional status levels were determined using satellite images (Moriondo et al., 2007). Grain yield could be predicted effectively using NDVI at an early growth stage (combination), but its accuracy decreases significantly during flowering.

Authors' Statement of Contribution

Idea/Hypothesis, Material, Method, Research, Data Processing, Data Analysis, Visualization, Executive/Consultant, Thesis Management, Original Drafting, Writing-Reviewing and Editing*, M. AYDOĞDU*; Data processing, Executive/Consultant, Writing-Reviewing and Editing, *K. AKAN*.

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Declaration of Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Research and Publication Ethics were followed in this study.

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