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Original scientific article

DEMONSTRATION THE EFFECTIVENESS OF NDVI WITH GGE BIPLOT MODEL IN DETERMINATION OF HIGH YIELDING DURUM WHEAT *(Triticum durum Desf.)* GENOTYPES

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The use of spectral indices such as normalised difference vegetation index (NDVI) is becoming an important element in the evaluation of physiological traits in cereal crops. Determining the correlation between spectral readings taken at different phenological stages of wheat plants and grain yield (GY) is crucial. This study aimed to demonstrate the effectiveness of NDVI in combination with the GGE biplot model in identifying high yielding durum wheat genotypes. Field experiments were conducted in multiple environments and growth stages to evaluate the relationship between NDVI and grain yield (GY). Twenty-five durum wheat genotypes were tested for two years under rainfed and supplementary irrigation conditions using a split plot experimental design. The results showed significant positive correlations between NDVI and GY, especially at the generative stages under rain-fed conditions. In contrast, NDVI at the grain-filling stage showed a weaker relationship with GY under supplemental irrigation. Genotypes exhibiting high NDVI values up to the stem elongation stage tended to have lower grain yields, emphasizing the importance of considering growth stage dynamics. GGE biplot analysis provided visual information on genotype-trait relationships, helping to identify genotypes with consistent performance in different environments. This study highlights

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that NDVI can be used to predict yield potential and guide selection in durum wheat breeding programs and the GGE biplot model serves as a valuable tool for genotype evaluation and selection.

Keywords: Durum wheat, greenseeker, GGE biplot, NDVI, yield

INTRODUCTION

The use of indices based on spectral reflection has become widespread in the measurement of physiological properties in cereals (MULLAN, 2012). These technologies allow for non-invasive and continuous monitoring of plant growth, providing valuable data on factors such as leaf area, biomass accumulation, and chlorophyll content. By analyzing this data, researchers and farmers can gain insights into the physiological processes occurring within the plants, helping them make informed decisions about crop management strategies and breeding programs (PRASAD *et al.,* 2006; HATFIELD and PRUEGER, 2010; LI and CHEN, 2011; BERNARDES *et al.,* 2012; KAYHAN *et al.,* 2020). Durum wheat *(Triticum durum Desf.)* was first cultivated in the Southeastern Anatolia Region, located in the North of the Fertile Crescent, and later spread to North Africa and the Northern Mediterranean (Figure 1) (ÇIĞ and KARAMAN, 2019; ÖZBERK and ÖZBERK, 2024).

Fig. 1. Map showing the Fertile Crescent region

Normalized vegetation index (NDVI) is extensively used to determine the correlation between the growth status of the cereal in different phenological periods and grain yield (GY) (MORGOUNOV *et al.,* 2014). Researchers reported a positive correlation between NDVI and both biomass and GY under fully irrigated conditions, and a high correlation with GY under dry conditions (GUTIERREZ-RODRIGUEZ *et al.,* 2004; MORGOUNOV *et al.,* 2014). NDVI readings at the beginning of the heading stage and during the grain filling period provide more accurate results to estimate the GY.

In addition, genotypes with erect canopy architecture give higher NDVI values than those with horizontal types (FENG and YANG, 2011; MORGOUNOV *et al.,* 2014). Early GY estimation is important in different environmental conditions. NDVI, one of the important spectral reflectance indices, can quickly predict crop growth potential non-destructively to the plant (MARTI *et al.,* 2007). NDVI values obtained in wheat have a high heritability and show high correlation with GY, depending on nitrogen concentration (RAUN *et al.,* 2001; PRASAD *et al.,* 2007; CRAIN *et al.,* 2012; HITZ *et al.*, 2017; SINGHA and MITRA, 2020; MITRA *et al.*, 2023).

The aim of this study was to determine the relationship between NDVI levels measured at different growth stages and GY in durum wheat. In addition, it was aimed to determine the appropriate plant development stages in which NDVI can be used as a selection parameter under irrigated and non-irrigated conditions.

MATERIALS AND METHODS

The research was conducted in 2014-2016 in Diyarbakır province of Türkiye, in 4 different environments (E1, E2, E3 and E4) and 12 different plant growth stages (Table 1).

Table 1. Information on plant development periods and environments

MN.	Developmental periods	Abbreviation	Growth stage	Environment	Altitude (m)
1	Seedling stage	SS	GS14	E1 (rainfed), E3 (rainfed)	599-610
2	Beginning of tillering stage	BTS	GS21	E1 (rainfed), E3 (rainfed)	599-610
3	Tillering stage	TS	GS23	E1 (rainfed)	599
4	Middle of tillering stage	MTS	GS24	E3 (rainfed)	610
5	End of tillering stage	ETS	GS26	E1 (rainfed), E3 (rainfed)	599-610
6	Beginning of stem elongation	BSE	GS31	E1 (rainfed)	599
7	Stem elongation	SE	GS34	E1 (rainfed), E3 (rainfed)	599-610
8	Flag leaf emergence	FLE	GS39	E3 (rainfed)	610
9	Booting stage	BS	GS47	E1 (rainfed), E3 (rainfed)	599-610
10	Heading stage	HS	GS57	E3 (rainfed), E4 (s. irrigation)	610
11	Milk stage	MS	GS73	E1 (rainfed), E3 (rainfed), E4 (s. irrigation)	599-610
12	Dough formation stage	BDFS	GS85	E1 (rainfed), E2 (s. irrigation)	599

GS: growth stage (ZADOKS *et al.*, 1974), MN.: measurement number, E1 and E3: rainfed conditions of first and second years respectively, E2 and E4: irrigated conditions first and second years respectively, s. irrigation: supplemental irrigation

The trial was set up in a split-plot experimental design with 3 replications under rainfed and supplemantary irrigation conditions. In the split plot design, the main plot (supplemental irrigation or rainfed) is further divided into genotypes (sub-plots). In both years, there was no need for irrigation in the pre-heading period due to the sufficient rainfall. Supplementary irrigation was applied to reach field capacity for soil water levels during GS57, GS73, and GS85 periods to prevent plants from experiencing drought stress. In the E2 and E4 environments, the differentiation was created by irrigation after the beginning of the heading period (Table 1). To determine the impact of irrigation on NDVI values, precise measurements were taken during the GS85 period in the first year and the GS57 and GS73 periods in the second year under irrigated conditions (Table 1). Twenty-five durum wheat genotypes, including both advanced lines and modern commercial varieties, were utilized as material for the study (Table 2). The plots were adjusted to be 5 meters long and 1.2 meters wide, resulting in a total area of 6 square meters.

This ensured optimal growth and yield for the crop. The seeds were sown using a seeder in six rows, with a density of 450 seeds per square meter.

In the first year of the study (2014-2015), precipitation levels exceeded the long-term average by approximately 100 mm. However, in the following season (2015-2016), precipitation levels were 67 mm lower than average (Table 3).
According to average temperature values (ANONOMY (2017a), temperatures were below the long-term averages in the months except october, december, january and february in the 2014-2015 growing season. In addition, in the 2015-2016 growing season, temperatures were above the long-term average in all months except december and january (Table 3). These data show that the 2015-2016 production season was warmer and more drought-prone than 2014-2015.

Table 2. Information on the genotypes used in the study

Genotypes	Breeder organization or origin
Altıntoprak-98	GAP International Agricultural Research and Training Center Directorate
Artuklu	GAP International Agricultural Research and Training Center Directorate
Aydın-93	GAP International Agricultural Research and Training Center Directorate
Ceylan-95	GAP International Agricultural Research and Training Center Directorate
Cesare	Progen Seed Inc.
Diyarbakır-81	GAP International Agricultural Research and Training Center Directorate
Dumlupınar	Transitional Zone Agricultural Research Institute
Fırat-93	GAP International Agricultural Research and Training Center Directorate
Gökgöl-79	Directorate of Trakya Agricultural Research Institute
Güneyyıldızı	GAP International Agricultural Research and Training Center Directorate
Fuatbey 2000	Eastern Mediterranean Agricultural Research Institute
Kunduru 1149	Transitional Zone Agricultural Research Institute
Meram-2002	Bahri Dagdas International Agricultural Research Institute
Pitagora	Maro Agriculture Inc.
Sarıbaşak	Eastern Mediterranean Agricultural Research Institute
Selçuklu-97	Bahri Dagdas International Agricultural Research Institute
Sham-1	Eastern Mediterranean Agricultural Research Institute
Sorgül	Landrace variety
Urfa 2005	Harran University Faculty of Agriculture
Tunca 79	Directorate of Trakya Agricultural Research Institute
Yelken 2000	Transitional Zone Agricultural Research Institute
Aday-1	CIMMYT
Aday-2	CIMMYT
Aday-3	CIMMYT
Aday-4	CIMMYT

CIMMYT: The International Maize and Wheat Improvement Center

The soils of the experimental area were unsalted, slightly alkaline, phosphorus and organic matter content were low (ANONYMOUS (2017b) (Table 4). According to standard practices, 60 *kg ha*$^{-1}$ nitrogen (N) and 60 *kg ha*$^{-1}$ phosphorus (P_2O_5) were applied together with planting in order to supplement the missing soil nutrients.

In addition, 80 *kg ha*$^{-1}$ N was given during the tillering period as top fertilizer. For the control of narrow and broad-leaved weeds, 50 g/L Pinoxaden + 12.5 g/L Cloquintocet-mexyl and 452.42 g/L 2,4-D 2-Ethylhexyl ester + 6.25 g/L Florasulam were used. Harvesting was done with a Wintersteiger parcel combine harvester and harvesting was carried out approximately 10 days later in the trial with supplemental irrigation than in the rainfed trial.

Table 3. Climatic data of the environments in which the study was conducted

Months	Average temperature (*ºC*)			Precipitation Amount (*mm*)		
	2014-2015 (E1 and E2)	2015-2016 (E3 and E4)	Long years	2014-2015 (E1 and E2)	2015-2016 (E3 and E4)	Long years
September	24.7	27.4	24.8	27.4	0	4.1
October	17.5	18.4	17.2	34.2	84.2	34.7
November	8.3	9.8	9.2	97.6	10.4	51.8
December	6.7	3.9	4.0	73.6	31.6	71.4
January	2.3	1.1	1.8	64.6	77.4	68.0
February	5.4	7.9	3.5	55.2	69.2	68.8
March	8.2	9.7	8.5	127.0	55.6	67.3
April	12.4	15.7	13.8	48.6	29.0	68.7
May	18.8	19.9	19.3	48.2	41.4	41.3
June	26.1	26.8	26.3	7.4	18.4	7.9
Total				583.8	417.2	484.0

Source: ANONYMOUS (2017a)

Table 4. Soil characteristics of trial area

Soil Structure	Total Salt (%)	Ph	Lime CaCO3 (%)	Phosphorus P_2O_5 (kg/da)	Organic Matter (%)	Saturation with water (%)
(2014-15) Clayey- loamy	0.25	7.8	6.3	1.28	0.676	77
(2015-16) Clayey- loamy	0.06	7.9	13.1	2.36	1.33	64

Source: ANONYMOUS (2017b)

Grain Yield (GY): The grains obtained after harvesting with a combine harvester were cleaned and weighed on a scale with ±0.001 g precision and then converted to kg ha^{-1}.

Normalized vegetation index (NDVI): NDVI values were determined by taking readings at 12 different plant development stages with an optical hand sensor (NTech. GreenSeeker Model 505) (Figure 2), which can be used practically between 11:00 and 15:00 in cloudless, clear and not rainy conditions (Table 1).

Statistical analyzes (ANOVA and least significant difference) were made using the JMP 5.0.1 package program (GOMEZ and GOMEZ, 1984), and GGE (genotype, genotype x environment) biplot graphics were made using the Genstat 12th package program (GENSTAT, 2009).

Fig. 2. NTech.GreenSeeker Model 505

RESULTS AND DISCUSSIONS

Significant differences among the genotypes were observed for grain yield at $p<0.01$ level (Fig. 3).

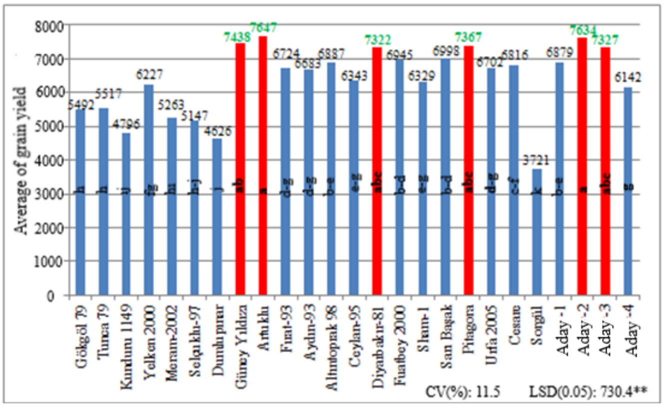

Fig. 3. Average grain yield of genotypes over all environments (kg ha^{-1})

According to all environmental averages, the highest grain yield (7647 kg ha^{-1}) was obtained from a variety of Artuklu durum wheat. The genotypes of Aday-2, Güneyyıldızı, Pitagora, Aday-3 and Diyarbakır-81 were in the same group as Artuklu variety. The lowest grain yield was obtained from Sorgül landrace durum wheat (3721 *kg* ha^{-1}).

Ceylan-95 (0.550), Diyarbakır-81 (0.560) and Tunca 79 (0.530) durum wheat cultivars had the highest NDVI at all plant growth stages in all environments (Table 5 and 6). Fuatbey 2000 (0.630), and Gökgöl 79 (0.630) were determined as genotypes with high values in E3 and E4 environments (Table 5 and 6).

Table 5. Average NDVI values for different plant growth stages in the E1 and E2 environments in the 2014-2015

Genotyp	SS (GS14) E1	BTS (GS21) E1	TS GS23) E1	ETS (GS26) E1	BSE (GS31) E1	SE (GS34) E1	BS GS47) E1	MS (GS73) E1	BDFS (GS85) Rainfed E1	BDFS (GS85) İrrigated E2	Average
Gökgöl 79	0.170	0.250	0.430	0.600	0.700	0.780	0.830	0.750	0.170	0.280	0.500
Tunca 79	0.210	0.360	0.460	0.640	0.760	0.790	0.840	0.770	0.150	0.300	0.530
Kunduru 1149	0.220	0.350	0.420	0.630	0.720	0.770	0.840	0.790	0.220	0.230	0.520
Yelken 2000	0.190	0.310	0.400	0.600	0.680	0.780	0.830	0.800	0.240	0.390	0.520
Meram-2002	0.170	0.290	0.390	0.570	0.700	0.790	0.840	0.810	0.230	0.410	0.520
Selçuklu-97	0.160	0.240	0.320	0.500	0.640	0.760	0.850	0.790	0.190	0.390	0.480
Dumlupınar	0.190	0.310	0.370	0.590	0.700	0.760	0.830	0.810	0.290	0.300	0.510
Güneyyıldızı	0.180	0.270	0.360	0.570	0.680	0.800	0.840	0.790	0.110	0.160	0.480
Artuklu	0.230	0.350	0.420	0.610	0.720	0.790	0.840	0.790	0.120	0.280	0.510
Fırat-93	0.240	0.350	0.450	0.600	0.720	0.790	0.840	0.780	0.160	0.300	0.520
Aydın-93	0.170	0.260	0.380	0.560	0.680	0.770	0.860	0.820	0.190	0.250	0.490
Altıntoprak 98	0.220	0.300	0.370	0.570	0.650	0.770	0.830	0.780	0.120	0.190	0.480
Ceylan-95	0.260	0.370	0.460	0.630	0.740	0.800	0.850	0.790	0.200	0.380	0.550
Diyarbakır-81	0.250	0.380	0.510	0.630	0.760	0.800	0.850	0.820	0.210	0.440	0.560
Fuatbey 2000	0.210	0.320	0.440	0.600	0.690	0.780	0.850	0.800	0.140	0.260	0.510
Sham-1	0.180	0.280	0.390	0.560	0.660	0.790	0.840	0.810	0.170	0.240	0.490
Sarıbaşak	0.150	0.230	0.310	0.490	0.580	0.750	0.850	0.780	0.200	0.320	0.470
Pitagora	0.170	0.260	0.350	0.520	0.660	0.790	0.840	0.790	0.130	0.230	0.470
Urfa 2005	0.190	0.280	0.410	0.580	0.670	0.770	0.850	0.800	0.180	0.230	0.500
Cesare	0.220	0.290	0.380	0.560	0.670	0.760	0.840	0.790	0.170	0.400	0.510
Sorgül	0.210	0.340	0.460	0.650	0.730	0.790	0.830	0.740	0.130	0.200	0.510
Aday -1	0.160	0.230	0.290	0.440	0.590	0.750	0.850	0.790	0.140	0.330	0.460
Aday -2	0.190	0.280	0.330	0.460	0.580	0.710	0.850	0.820	0.170	0.410	0.480
Aday -3	0.160	0.240	0.300	0.490	0.630	0.750	0.840	0.810	0.210	0.360	0.480
Aday -4	0.170	0.270	0.390	0.550	0.660	0.750	0.840	0.780	0.160	0.290	0.490
General	0.190	0.300	0.390	0.570	0.680	0.770	0.840	0.790	0.180	0.300	
LSD $_{(0.05)}$:	0.040**	0.060**	0.090**	0.080**	0.060**	0.040**	0.020**	0.020**	0.030**	0.010**	
CV (%) :	17.80	18.40	18.90	12.10	7.70	4.10	1.60	3.40	11.40	19.80	

SS: Seedling stage, BTS: Beginning of tillering stage, TS: Tillering stage, ETS: End of tillering stage, BSE: Beginning of stem elongation, SE: Stem elongation, BS: Booting stage, MS: Milk stage, BDFS: Dough formation stage, E1: rainfed conditions, E2: irrigated conditions. The first 7 genotypes are winter and the other genotypes are spring characters.

Table 6. Average NDVI values for different plant growth stages in the E3 and E4 environments in the 2015-2016 growing year

Genotype	SS (GS14) E3	BTS (GS21) E3	MTS (GS24) E3	ETS (GS26) E3	SE (GS34) E3	FLE (GS39) E3	BS (GS47) E3	HS (GS57) Rainfed E3	HS (GS57) İrrigated E4	MS (GS73) Rainfed E3	MS (GS73) İrrigated E4	Average
Gökgöl 79	0.150	0.290	0.330	0.580	0.790	0.840	0.850	0.840	0.830	0.710	0.710	0.630
Tunca 79	0.170	0.330	0.340	0.570	0.760	0.830	0.850	0.850	0.840	0.680	0.710	0.630
Kunduru 1149	0.210	0.300	0.32	0.610	0.780	0.810	0.830	0.780	0.810	0.670	0.740	0.620
Yelken 2000	0.170	0.290	0.320	0.560	0.710	0.800	0.840	0.790	0.820	0.590	0.710	0.600
Meram-2002	0.160	0.320	0.310	0.570	0.760	0.810	0.840	0.800	0.840	0.440	0.700	0.600
Selçuklu-97	0.170	0.260	0.320	0.600	0.770	0.820	0.840	0.810	0.840	0.510	0.730	0.610
Dumlupınar	0.200	0.300	0.300	0.570	0.720	0.810	0.830	0.790	0.800	0.720	0.760	0.620
Güneyyıldızı	0.220	0.280	0.400	0.650	0.800	0.830	0.840	0.810	0.820	0.380	0.690	0.610
Artuklu	0.210	0.280	0.370	0.650	0.770	0.820	0.830	0.810	0.810	0.460	0.690	0.610
Fırat-93	0.210	0.370	0.370	0.670	0.790	0.810	0.820	0.790	0.800	0.380	0.650	0.600
Aydın-93	0.150	0.260	0.320	0.590	0.750	0.800	0.840	0.810	0.820	0.630	0.740	0.610
Altıntoprak 98	0.210	0.320	0.370	0.630	0.780	0.820	0.830	0.790	0.800	0.400	0.700	0.600
Ceylan-95	0.210	0.300	0.430	0.700	0.800	0.830	0.850	0.830	0.820	0.570	0.710	0.640
Diyarbakır-81	0.220	0.360	0.450	0.730	0.820	0.840	0.860	0.850	0.850	0.680	0.750	0.670
Fuatbey 2000	0.240	0.280	0.370	0.630	0.780	0.820	0.840	0.830	0.830	0.550	0.710	0.630
Sham-1	0.160	0.260	0.250	0.520	0.690	0.770	0.820	0.820	0.810	0.470	0.740	0.570
Sarıbaşak	0.180	0.280	0.320	0.550	0.740	0.800	0.820	0.800	0.820	0.450	0.700	0.590
Pitagora	0.160	0.300	0.310	0.600	0.770	0.810	0.840	0.830	0.820	0.630	0.720	0.620
Urfa 2005	0.150	0.210	0.280	0.520	0.710	0.790	0.840	0.810	0.830	0.480	0.740	0.580
Cesare	0.220	0.300	0.330	0.570	0.710	0.790	0.830	0.790	0.820	0.560	0.700	0.600
Sorgül	0.220	0.320	0.400	0.640	0.810	0.830	0.840	0.800	0.790	0.400	0.720	0.620
Aday -1	0.170	0.260	0.260	0.530	0.710	0.780	0.840	0.810	0.820	0.540	0.700	0.580
Aday -2	0.180	0.250	0.250	0.550	0.690	0.760	0.830	0.800	0.810	0.480	0.700	0.570
Aday -3	0.180	0.270	0.330	0.570	0.730	0.780	0.830	0.790	0.820	0.420	0.730	0.590
Aday -4	0.230	0.330	0.390	0.620	0.750	0.820	0.820	0.770	0.830	0.420	0.650	0.600
General average	0.190	0.290	0.330	0.600	0.760	0.810	0.840	0.810	0.820	0.530	0.710	
LSD $_{(0.05)}$:	0.030**	0.050**	0.050**	0.080**	0.050**	0.030**	0.020**	0.030**	0.020**	0.040**	0.040**	
CV (%) :	14.90	14.10	12.60	11.90	6.20	3.50	2.00	2.80	1.60	5.80	1.60	

MTS: Middle of tillering stage, FLE: Flag leaf emergence, HS: Heading stage, E3: rainfed conditions, E4: irrigated conditions. The first 7 genotypes are winter and the other genotypes are spring characters.

Evaluation of Genotype, Genotype x Trait Relationships

The vector representation model of GGE biplot analysis has been used by many researchers to evaluate the genotype-trait relationship (YAN and TINKER, 2005; NEISSE *et al.*, 2018; KENDAL *et al.*, 2019; KARAMAN, 2022). This can help breeders identify which genotypes are best suited for specific traits and which traits are most influenced by certain genotypes. According to this model, genotype variation increases as vector length increases and decreases as vector length decreases (YAN and KANG, 2003; YAN *et al.*, 2007).

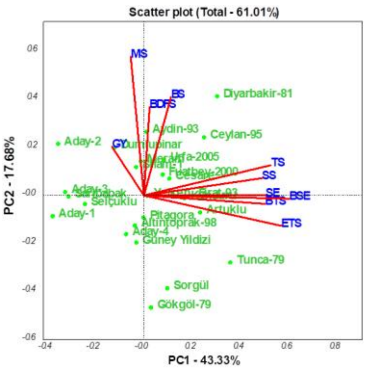

Fig. 4. In E1 rainfed conditions, genotype-trait with vectors

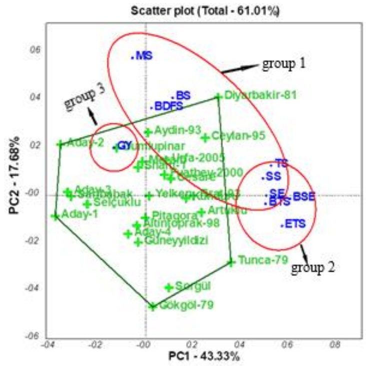

Fig. 5. In E1 rainfed conditions, representation of relationships with polygon and groups

The size of the angle between the vectors determines the level of association between the investigated traits. For example, increasing the angle value decreases the positive correlation, on the contrary, decreasing the angle value means that there is a strong positive relationship between the two traits. A 90° angle value indicates there is no correlation. In addition, the genotype closest to the vector of any trait can be interpreted as the ideal genotype for that trait. This means that the closer the angle is to 0°, the stronger the positive correlation between the features. Conversely, an angle close to 180° indicates a strong negative correlation between the features (YAN and THINKER, 2006; KARAMAN, 2019).

In this framework, it was observed that there was a positive correlation between GY and NDVI in the MS, BDFS and BS periods and a negative correlation between NDVI measured in TS, SS, SE, BSE, BTS and ETS periods in E1 environment, representing rain-fed conditions. These findings suggest that the relationship between GY and NDVI is influenced by the stage of the growing season and environmental conditions (Fig. 4).

When interpreting the genotype-trait relationship with polygons and groups, the genotype on the polygon's diagonal is optimal for traits closest to the relevant region. Furthermore, the traits within the same group exhibit a robust relationship (YAN and KANG, 2003). Based on these concepts, three distinct groups were formed in the E1 environment, which represents rain-fed conditions (Fig. 5). According to the Figure 5, NDVI measurements in all periods were clustered in Groups 1 and 2, while GY was alone in Group 3. Diyarbakır-81 in the 1st group, Tunca-79 in the 2nd group and Aday-2 in the 3rd group were classified as the highest performing genotypes in terms of the related traits because they were located on the diagonals. These genotypes exhibited superior performance compared to others in their respective groups, showcasing their potential for further research (Fig. 5).

The genotype of Aday-2, which has one of the greatest grain yields among all genotypes, placed first in terms of NDVI measurements during the BS and MS periods in the E1 environment, as well as the BDFS period in the E2 environment. This suggests that genotypes with high NDVI during these periods may be correlated with high grain yield production (Fig. 4, 5, 6 and 7).

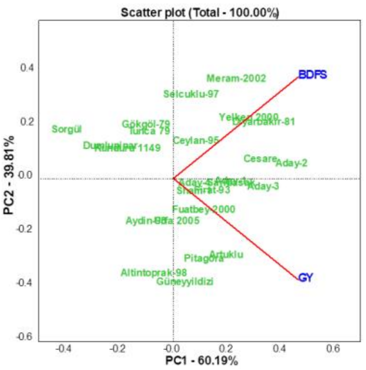

Fig. 6. E2 supplemental irrigation conditions, genotype-trait relationship with vectors

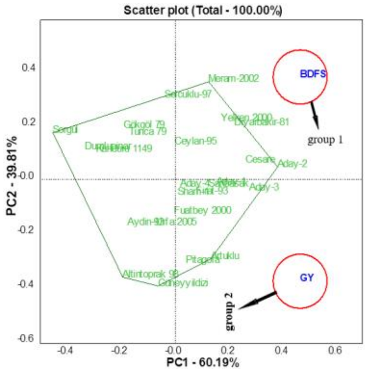

Fig. 7. E2, supplemental irrigation conditions indicated by polygon and groups

In the E2 environment, where additional irrigation was applied to eliminate drought stress, it was observed that GY was not related with BDFS and these traits were in 2 different groups (Fig 6 and 7). Among the durum wheat genotypes, Meram-2002, Aday-2, and Diyarbakır-81 were identified as having the highest potential in terms of NDVI value in the first group. In the second group, Artuklu, Güneyyıldızı, and Aday-2 were determined to have the highest potential in terms of GY (Fig. 7).

In the E3 environment, representing rain-fed conditions, there is a positive correlation between GY and MS, HS, BS period NDVI measurements. This shows that NDVI measurements in the reproductive growth stages are related to yield, as in E1 conditions (Fig. 8). It has been determined that there are 5 different groups in E3 (Fig. 9). There are a strong positive relationship between the characteristics in the same group (YAN and KANG, 2003). It was determined that GY, HS, BS, BTS, FLE and SE were in the 1st group, ETS and MTS were in the 2nd group, MTS was in the 3rd group, SS was in the 4th group, and GY and MS were in the 5th group (Fig. 9).

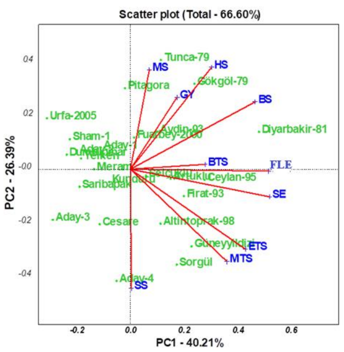

Fig. 8. E3 rainfed conditions, genotype-trait relationship with vectors

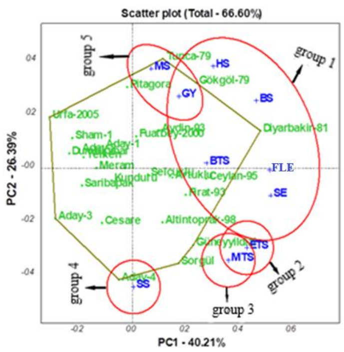

Fig. 9. E3 rainfed conditions, showing with polygon and groups

NDVI measurements in groups 1 and 5 were associated with GY, especially MS and HS period NDVIs showed strong correlation to GY. A strong positive relationship was detected between GY and HS in the E4 environment with supplemental irrigation applied (Figures 10 and 11).

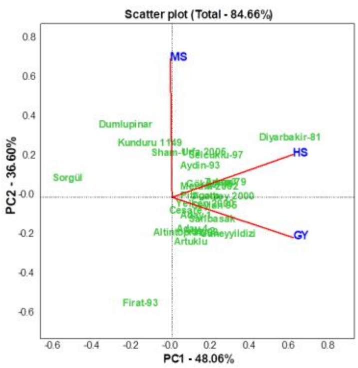

Fig. 10. E4 irrigation conditions, genotype-trait relationship with vectors

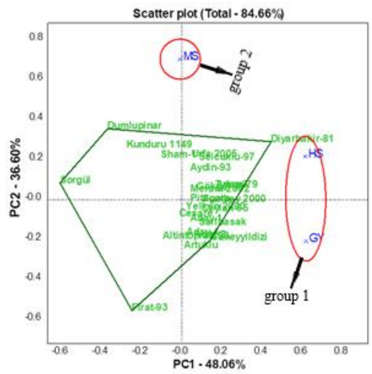

Fig. 11. E4, supplemental irrigation conditions indicated by polygon and groups

In their study, MARTI *et al.* (2007) found a link between grain yield (GY) and normalized difference vegetation index (NDVI) during the grain filling phase. They observed that the correlation was particularly stronger during the heading period compared to the booting period. Our study yielded comparable outcomes under rainfed conditions, as depicted in Figures 4 and 8. Furthermore, it has been noted that there is a significant positive relationship between the NDVI of booting and heading stages and grain yield in various conditions (Fig. 4, 8, 9, 10, and 11).

It has been determined that NDVI measurements and GY are in 2 different groups in the E4 environment. HS and GY were in the first group and MS was just alone in the second group. The grouping of GY and HS into the same category signifies a robust positive correlation between the two variables, whereas the segregation of MS from GY implies a relatively weak correlation (Fig. 10 and 11).

Among the cultivars studied, Güneyyıldızı showed the highest correlation with HS NDVI measurement and GY, while Dumlupınar was found to be the most related cultivar in terms of MS NDVI measurement. Furthermore, Diyarbakır-81 exhibited a close relationship with all traits in both groups. According to a study by MART *et al.* (2007), there is a high correlation between NDVI and GY at the GS73 (MS) stage and a moderate correlation at the stem elongation stage. The study suggests that NDVI measurements can be particularly useful, especially during the stem elongation stage (MARTI *et al.*, 2007).

ROYO *et al.* (2003) and MARTI *et al.* (2007) found a stronger correlation between NDVI measurements during milk formation and GY compared to other plant growth stages. Our research validated these results and established a favorable correlation between NDVI measurements during the booting (GS47), heading (GS57), and milk (GS85) development stages with grain yield (GY). Post-booting NDVI measurements exhibited a robust positive correlation with grain yield in rainfed conditions, although the correlation was less pronounced in the presence of supplemental irrigation. These findings indicate that NDVI can be a valuable tool for monitoring crop growth and predicting yield potential.

CONCLUSION

Analysing the relationship between grain yield and normalized difference vegetation index (NDVI) at various growth stages has provided critical information on the physiological status and productivity potential of durum wheat. The study revealed that genotypes with high NDVI values up to the stem elongation stage had the lowest grain yield, as NDVI generally correlates with lower yield before and during the stem elongation stage. GGE biplot graphs showed a positive and strong correlation between grain yield and NDVI, especially in the generative stage (BS, HS, MS, and BDFS) under rainfed conditions. There was a strong positive correlation between grain yield and NDVI measurements at HS and a weak negative correlation with grain filling stage measurements under supplementary irrigation conditions. The study concluded that genotypes with high NDVI values maintain similar responses to different environments, making them useful for grain yield estimation and selection in breeding programs. The GGE biplot model was found to be visually helpful in finding durum wheat genotypes that could produce a high yield, which made the selection process easier.

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EFIKASNOST NDVI SA GGE BIPLOT MODELOM U ODREĐIVANJU GENOTIPA VISOKO PRINOSNE DURUM PŠENICE (*Triticum durum* Desf.)

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Izvod

Upotreba spektralnih indeksa kao što je indeks normalizovane razlike vegetacije (NDVI) postaje važan element u proceni fizioloških osobina žitarica. Određivanje korelacije između spektralnih očitavanja uzetih u različitim fenološkim fazama biljaka pšenice i prinosa zrna (GI) je ključno. Ova studija je imala za cilj da pokaže efikasnost NDVI u kombinaciji sa GGE biplot modelom u identifikaciji genotipova durum pšenice visokog prinosa. Eksperimenti na terenu su sprovedeni u više okruženja i faza rasta da bi se procenio odnos između NDVI i prinosa zrna (GI). Dvadeset pet genotipova durum pšenice je testirano dve godine u uslovima kišnog režima i dopunskog navodnjavanja korišćenjem eksperimentalnog dizajna podeljenih parcela. Rezultati su pokazali značajnu pozitivnu korelaciju između NDVI i GI, posebno u generativnim fazama u uslovima režima kišom. Nasuprot tome, NDVI u fazi punjenja zrna pokazao je slabiji odnos sa GI pod dodatnim navodnjavanjem. Genotipovi koji pokazuju visoke vrednosti NDVI do faze elongacije stabljike imaju tendenciju nižeg prinosa zrna, naglašavajući važnost razmatranja dinamike faze rasta. GGE analiza biplota pružila je vizuelne informacije o odnosima genotip-osobina, pomažući da se identifikuju genotipovi sa doslednim performansama u različitim okruženjima. Ova studija naglašava da se NDVI može koristiti za predviđanje potencijala prinosa i usmeravanje selekcije u programima oplemenjivanja durum pšenice, a GGE biplot model služi kao dragoceno sredstvo za procenu i selekciju genotipa.

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