

Efficiency of yield-based tolerance indices to identify suitable genotypes for stress and non-stress environments

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Abstract

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The present study investigated the performance of popular crop breeding indices for assessing abiotic stress tolerance in selected wheat cultivars. The working hypothesis was to identify those indices whose application allows the identification of varieties possessing tolerance to drought in combination with the highest possible yield productivity. Three datasets were analyzed, formed from agroecological field trials in which different reported groups of cultivars, locations, and seasons were included. From the grain yield values of each genotype in contrasting environmental conditions, breeding indices were calculated to assess tolerance to abiotic stress. Their effectiveness and applicability for cultivar assessment were evaluated by direct comparison using correlational, principal component, and cluster analyses. Rank correlations between indices and cultivar grain yield varied across the databases. Correlations of indices with yield under favorable conditions showed strong variation among the individual datasets. Only a few indices (GMP, STI, MRP) maintained reliably high and valid correlations with grain yield. A preponderance of the calculated indices (excluding ATI and SSPI) had high positive correlations with yield under stress, maintaining these high levels across all three datasets. The high performance of the GMP, STI, and MSTI indices was confirmed by a specific assessment of cultivar differences in 40 ABC. Almost all of the investigated indices (except TOL, ARI, and SSPI) were significantly more effective and applicable for assessing stress tolerance than for the conditions under which the maximum possible grain yield was formed. Determining the most valuable cultivars exhibiting high yield under both types of conditions was possible by applying the GMP, STI, MSTI, or SNPI indices.

Keywords: breeding indices; stress tolerance; stress and non-stress environments; grain yield; common wheat

Abbreviations: GY – grain yield; (TOL) – Tolerance Index; (MP) – Mean Productivity; (GMP)-Geometric Mean Productivity; (HM) – Harmonic Mean; (YSI)-Yield Stability Index; (SSI) – Stress Susceptibility Index; (STI) – Stress Tolerance Index; (YI) – Yield Index; (RSI) – Relative Stress Index; (MRP) – Mean relative performance; (ATI) – Abiotic Tolerance Index; (SSPI) – Stress Susceptibility Percentage Index; (MSTI) – Modified Stress Tolerance Index; (SNPI) – Stress and Non-stress Production Index; (PCI) – Potential Capacity Index; (RCI) – Resilience Capacity Index

Introduction

The estimation of cultivar grain yield for breeding purposes under diverse environmental conditions has always been the focus of numerous studies (Van Ittersum et al.,

2013; Tsenov et al., 2015; Thiry et al., 2016). Wheat has been successfully grown in all parts of the planet under highly diverse environmental conditions (Carver et al., 2009). At least one-third of its area is located in areas where abiotic stress during vegetation and is an annual occurrence (Reynolds et

al., 2016). In this extensive climatic framework, it is crucial to gather information on the performance realization of the variety in the specific conditions of the region where abiotic stress is present (Tsenov et al., 2011, El-Sabagh, 2019).

The assessment of genotype under abiotic stress is done using breeding indices (Thiry et al. 2016; Sharma et al., 2022). The values of these indices are based on the difference between the yield under favorable conditions and that in the presence of abiotic stress as cold, drought or heat (Pour-Aboughadareh et al., 2019).

Sofi et al. (2018) define these breeding indices as quantitative measurements that characterize genotype response to stress, using yield data from multiple environments. They are *per se* potential indicators of genotype differences in biological response to drought. Each index is easier to apply and more informative than raw grain yield data. For example, if the difference in yield reduction ($Y_p - Y_s$) due to stress is used, selection may be inefficient due to the likelihood of highlighting low-yielding varieties, with little yield difference between the two groups of conditions. Expressed in terms of different ratios of yield under the two sets of conditions, the different indices reflect tolerance to stress, but this may vary depending on the particular choice (Mittal and Singh, 2021; Sofi et al., 2021).

According to the final result of the genotype response to stress and no stress, cultivars could be classified into several principle groups (Fernandez, 1992; Thiry et al. 2016): Class A: cultivars that display high productivity under favorable and stressful conditions belong to this group. Such genotypes are rarely detected because high yield is difficult to combine with high stress tolerance; Class B: Genotypes that display high productivity under favorable conditions without stress, but not in the presence of stress. These genotypes have high productivity under favourable conditions, but possess relatively low stress tolerance; Class C: varieties that exhibit high grain yield only under stress, i.e. possess high tolerance but not satisfactory productivity; Class D: genotypes of this class possess low levels of productivity and stress tolerance compared to the others in the group studied.

The informativity of any single index is directly dependent on several specific factors: the experimental conditions, the particular characteristics of the cultivar group, and the magnitude of difference (contrast) between the stress-free and stressed conditions (Bennani et al., 2017; Mohammadi, 2019; Lamba et al., 2023). This is the reason why researchers use a distinct set of indices to obtain the desired information in terms of simultaneous evaluation of the variety on grain yield and stress tolerance.

The possibility of using the different known indices is evidenced by the correlations that each has with yields un-

der favorable conditions (Y_p) and under abiotic stress (Y_s), as well as between them (Alhag et al., 2021; El-Refae et al., 2023). Many authors pay primary attention to yield relationship indices (Y_s) due to increased breeding interest, to discover mainly high tolerant cultivars that under stress guarantee realization and higher grain yield (Mohammadi and Geravandi, 2024). In fact, it is the absence of conditions for the realization of high productivity in different regions of the world, that has led researchers to look for ways to assess yield differences under different degrees of stress occurrence, applying various indices (Sofi et al., 2018; Mohammadi, 2019). Some of the information on the performance of the indices is obtained from the application of principal component analysis (PCA). The information that is submitted in the interpretation of the results is so specific and different, the set of indices that are informative is very different (El-Refae et al., 2023; Silva et al., 2023).

The available information on the applicability of individual indices in this direction shows that some of them, such as Stress Tolerance Index (STI), Mean Productivity (MP), Geometric Mean Productivity (GMP) and Harmonic Mean (HM) manifest a high positive correlation with grain yield in both groups of conditions (Tsenov et al., 2017; Vaezi et al., 2020; Fatehi et al., 2022), making them in a sense universally applicable. For other indices, such as Tolerance Index (TOL), Stress Susceptibility Index (SSI), Yield Index (YI), Relative Stress Index (RSI), Mean relative performance (MRP), and others, the correlations to the two types of conditions are fundamentally opposite, which in practice makes them low effective for evaluating the variety in both types of conditions (Alhag et al., 2021; Mahdavi et al., 2023).

For some of the other known indices, information is rather limited and contradictory and in many ways theoretical (Sofi et al., 2018; Lamba et al., 2023). In Bulgaria, Ivanova et al. (2011); Tsenov et al. (2012); Tsenov et al. (2017) found several of the 8 indices they studied could be effectively applied to such an assessment of the country's climatic conditions.

Information on the usefulness of each of the indices in different studies is variable, which is a prerequisite for establishing a specific set of indices that would provide a parallel assessment of genotype in both types of environmental conditions.

Thus, the objective of this study is to critically analyze the informativeness of known indices for assessing stress tolerance in common wheat cultivars. The working hypothesis is to identify those of them, the use of which allows to identify varieties possessing a compromise combination of high productivity under favorable and the highest possible tolerance under stressful environmental conditions

Material and Methods

General information

A sample of three data sets, denoted here as 40 ABC, 27 PR and 24 PhD, was used for the purpose of the study. General information about the field trials from which data were obtained, according to location, number of varieties included and study periods, are presented in Table 1.

At each location, the field experiment was laid out in a block of 3 replications (at 40 ABC – in four), with the size of the experimental plot of 10 m² (12 rows, 8 m in length, 10.5 cm between rows). Planting density was the national standard of 500 seeds m⁻². Trials were fertilized with 170 kg/ha N (active substance), twice before sowing and in phase (Zadok's scale of wheat Z29) and 120 kg/ha P (active substance) – once before sowing. During the active growing season, in order to prevent unwanted effects from diseases and insects, crop protection was applied, including a single application of herbicide and insecticide, as well as a fungicide treatment, twice in phases (Zadok's scale of wheat Z33) and (Zadok's scale of wheat Z51) (Zadoks et al., 1974). The data collected from each plot includes the trait grain yield (GY).

Meteorological conditions

From the three datasets, those from locations where the grain yield throughout the relevant research period showed the most contrasting differences were selected (Table 2). Undoubtedly, they were caused by the soil-climatic features of locations, and the conditions of the season, through their meteorological distinction, bring additional variation in grain yield. This provided a real opportunity to evaluate the performance of each variety from the relevant group of datasets. The assessment could include both the realization of the productive potential of the variety under favourable (Y_p) and under stressful environmental conditions (Y_s). The

results for the grain harvest at the Dobrich location due to their high level of realization (800–950 kg/ha), because of optimal combinations between the weather conditions of the respective seasons, were considered favourable, and at the other locations as stressful.

Statistical methods and approaches

The tolerance of the cultivars was evaluated by calculating seventeen different indices for evaluating the tolerance of the genotype to drought, some of which are widely used (Table 3).

According to the type of data, they include and the way they were calculated, the breeding indices would be tentatively grouped as follows: *i*). *Simple* – contain different ratios between the values of the characteristic under favourable (Y_p) and stressful conditions (Y_s). Through them, the reaction of the genotype in the environmental conditions was evaluated, without taking into account the other genotypes in the studied group; *ii*). *Complex* – contain different ratios between the values of the trait under favourable (Y_p) and stressful conditions (Y_s), which were compared to the group averages of both types of conditions (Y_p and Y_s), which allowed the direct comparison between all studied varieties; *iii*). *Composite (derivative)* – contain elements from some of the indices from the first two groups or were new combinations of the values of the variety characteristic and/or the group averages of the two types of conditions; *iv*). *Group (summarized)* – averaging the indices associated with the first group or the second group separately.

The indices of the first and second groups were obtained using the statistical package i-PASTIC (Pour-Aboughadareh et al., 2019). All other indices were calculated using the formulas of the authors who published them, as original for the first time (Table 3). The extracted values of each index were ordered (ranked), according to the number of varieties participating in the respect experiment. Statistical analyses were

Table 1. General information on the levels of the main factors – Location (A), Year of testing (B) and Genotype (C) of the conducted field experiments of the Datasets

Location (A)	Coordinates		Altitude	Years (B)	Genotypes (C)
	N	E			
24 PhD Data Set					
Dobrich	43°38'47"	27°48'40"	248	2009–2012	
Plovdiv, Agri. University	42°08'13"	24°48'22"	155		Cultivars 24
27 PR Data Set					
Dobrich	43°38'47"	27°48'40"	248	2016–2018	
Radnevo, Stara Zagora	42°17'25"	25°58'26"	140		Cultivars 27
40 ABC Data Set					
Dobrich	43°38'47"	27°48'40"	248	2017–2019	
Straldja, Yambol	42°35'25"	26°39'06"	150		Cultivars 40

Source: Authors' own elaboration

made on their rank values (ranks), that were effective in dividing the cultivars into groups according to the degree of their stress tolerance, according to the principled approaches of Fernandez (1992) and Thiry et al. (2016). A comparison of the Spearman rank correlations of the indices was made by individual datasets to determine whether there were any fundamental differences in the results. Their summary results were based on the average values from the three datasets. All statistical analyses were performed using the software packages SPSS 19, Statgraphics XVIII and JMP 14.

Results

For each dataset, grain yield was significantly affected by environmental factors, genotype, and their interaction. An exception was noted in 24 PhDs, regarding the interaction of the factors “Year x Cultivar”. An interaction between location conditions and year was valid for all parameter values without exception for every single dataset. All these effects determined the observed significant differences in the magnitude of grain yield (Table 2).

To determine which of the indices should be applied for evaluation, their rank values were compared with those of grain yield under both groups of favourable (Yp) and stress (Ys) conditions. According to the objective, it was important to identify those indices, whose correlations with yield were high under both types of conditions.

The results of Spearman correlation interdependencies between index ranks and those of yield ranks in favourable conditions (Yp) differed significantly (Table 3). The differences in the correlation values were in two aspects: between the indices themselves and between their values in the individual datasets. The correlations between the yield ranks in both sets of conditions were positive. They ranged from 0.27

to 0.47 across datasets, with only 24 PhDs having a significant association. This showed how important it was to make a specific assessment for each individual field experience, even when the differences between the both sets of conditions showed similar values.

Several indexes showed negative correlations with (Yp) in all three datasets – TOL, SSI, YSI and RSI, but they were relatively low and unreliable. Naturally, they could not be used to achieve the set goal.

All other indices had a positive relationship with yield, but they varied in magnitude and reliability across datasets. For example, the YI and SSPI indices had consistently positive correlations with yield, but it was either very low (24 PhD, 40 ABC) or unreliable (27 PR). Just a few indexes showed a positive correlation with grain yield (Yp), regardless of the dataset. These were the MP, GMP, NM, STI, MRP, MSTI, SNPI and PCI indices. These correlations were indeed reliable, but their validity (R^2) varied between datasets.

In a detailed comparison of the values of the coefficient of determination of these indexes in the individual datasets, it became apparent that only two of them – GMP and MRP had correlations that were positive and valid for at least about 40% of the respective cultivar group of the individual datasets. The indices from the mentioned group with positive correlations (MP, NM, STI, MSTI, SNPI, and PCI) showed marked variability across datasets and in correlation values as well as their validity. Therefore, they could also be successfully applied in specific field trials, in case their validity is high enough, such as that of 24 PhDs.

In the correlations of indices with yield under stress (Ys) a similar complex pattern of change was observed (Fig.1). Only two indices (ATI and SSPI) showed negative correlations with grain yield, reliable in two of the three datasets.

Table 2. Relative changes (%) between grain yields and the main meteorological parameters in Dobrich and the corresponding locations in the individual data sets

Dataset	Trait, Parameter	GY	ADT	SP	GDD
	Location	t ha ⁻¹	C ⁰	mm m ⁻²	C ⁰
40 ABC	Dobrich	9.45 b	8.0 a	416 b	2388 a
	Straldja	6.14 a	9.9 b	303 a	2790 b
	Relative changes, %	- (35.0)	- (19.2)	- (27.2)	+ (16.8)
27 PR	Dobrich	8.14 b	8.2 a	456 b	2200 a
	Radnevo	5.90 a	9.4 b	355 a	2660 b
	Relative changes, %	- (27.6)	- (12.8)	- (22.1)	+ (20.9)
24 PhD	Dobrich	8.50 b	8.2 a	429 b	2150 a
	AU, Plovdiv	6.86 a	9.7 b	342 a	2630 b
	Relative changes, %	- (28.7)	- (15.5)	- (20.3)	+ (22.3)

GY – grain yield, ADT – Monthly Average Daily air Temperature, SP – Sum of Precipitations (during the wheat growing period), GDD – Growing Degree Days (during the wheat growing period) RC – relative changes, a, b – Multiple Range Tests by Fisher’s least significant difference (LSD)

Source: Authors’ own elaboration

Table 3. Brief information on drought tolerance indices used

Index	Formula	Reference
Tolerance Index	$TOL = Y_p - Y_s$	<i>Rosielle and Hamblin (1981)</i>
Mean Productivity	$MP = Y_p - Y_s / 2$	<i>Rosielle and Hamblin (1981)</i>
Geometric Mean Productivity	$GMP = \sqrt{Y_s * Y_p}$	<i>Fernandez (1992)</i>
Harmonic Mean	$HM = 2(Y_s * Y_p) / Y_s + Y_p$	<i>Bidinger et al. (1987)</i>
Yield Stability Index	$YSI = Y_s / Y_p$	<i>Bouslama and Schapaugh (1984)</i>
Stress Susceptibility Index	$SSI = 1 - (Y_s + Y_p / 1 - (Y_s / Y_p))$	<i>Fischer and Maurer (1978)</i>
Stress Tolerance Index	$STI = Y_s * Y_p / (Y_p)^2$	<i>Fernandez (1992)</i>
Yield Index	$YI = Y_s / Y_s$	<i>Gavuzzi et al. (1997)</i>
Relative Stress Index	$RSI = Y_s / Y_p / Y_s / Y_p$	<i>Fischer and Wood (1979)</i>
Mean relative performance	$MRP = (Y_s / Y_s) + (Y_p / Y_p)$	<i>Ramirez and Kelly (1998)</i>
Abiotic Tolerance Index	$ATI = TOL / Y_p / Y_s * GMP$	<i>Moosavi et al. (2008)</i>
Stress Susceptibility Percentage Index	$SSPI = Y_p - Y_s / 2 Y_s * 100$	<i>Moosavi et al. (2008)</i>
Modified Stress Tolerance Index	$MSTI = STI * Y_p^2 / Y_p^2 * Y_s^2 / Y_s^2$	<i>Farshadfar and Elyasi (2012)</i>
Stress Non-stress Production Index	$SNPI = \sqrt[3]{(Y_p + Y_s / Y_p - Y_s)} * \sqrt[3]{(Y_p * Y_s * Y_s)}$	<i>Farshadfar and Elyasi (2012)</i>
Potential Capacity Index	$PCI = RC + TOL + MP + GMP + HM / 5$	<i>Thiry et al. (2016)</i>
Resilience Capacity Index	$RCI = SSI + STI + YI + YSI + RSI / 5$	<i>Thiry et al. (2016)</i>

Y_p – Yield under optimal conditions of the cultivar, Y_p – Average yield under optimal conditions of the whole group of cultivars, Y_s – Yield under stress conditions of the cultivar, Y_s – Average yield under stress conditions of the group of cultivars

Source: Authors' own elaboration

Table 4. Analysis of variances according to the factors location and season of grain yield and the main meteorological parameters (Type III Sums of Squares)

Source of variation	GY		ADT		SP		GDD	
	MS	<i>p-value</i>	MS	<i>p-value</i>	MS	<i>p-value</i>	MS	<i>p-value</i>
Data set	24 PhD							
A: Location	228.39	0.000	476.46	0.000	60516	0.045	2592510	0.000
B: Year	263.76	0.000	106.62	0.000	3213760	0.179	22785.3	0.000
C: Cultivar	0.75	0.040						
A x B	59.73	0.000	91.92	0.000	39888	0.000	5304.86	0.000
A x C	0.48	0.034						
B x C	0.38	0.666						
Data set	27 PR							
A: Location	408.83	0.000	2662.56	0.000	16745.19	0.000	88779.99	0.000
B: Year	253.46	0.000	1020.96	0.000	15542.31	0.000	9349.25	0.000
C: Cultivar	2.09	0.000						
A x B	27.19	0.000	779.04	0.000	17959.23	0.000	14414.57	0.000
A x C	1.01	0.000						
B x C	0.44	0.000						
Data set	40ABC							
A: Location	871.25	0.000	26.89	0.003	2725.68	0.023	121032.0	0.000
B: Year	1401.23	0.000	7.45	0.013	702.54	0.002	7973.1	0.000
C: Cultivar	6.58	0.000						
A x B	61.83	0.000	5.23	0.043	1389.01	0.000	6383.4	0.000
A x C	4.50	0.006						
B x C	8.82	0.000						

GY – grain yield, ADT – Annual average Daily air Temperature, SP – Sum of Precipitations (during the wheat growing period), GDD – Growing Degree Days (during the wheat growing period)

Source: Authors' own elaboration

All other indices had a strong positive correlation with stress yield that varied by dataset, but remained sufficiently high and valid. According to their modification, they can be conditionally divided into two groups: 1) with a consistently high and valid correlation regardless of the data set (MP, GMP, HM, STI, MRP, YI, MSTI, SNPI, PCI, RCI) and 2), with a high positive and sufficiently valid correlation (TOL, SSI, YSI, RSI), except for a dataset of 24 PhD. The second set of indices had high correlations that were valid for only about 35% of the group of 24 doctoral students. They can also be successfully used to assess genotype tolerance, but with the caveat of low representativeness.

In 24 PhDs, PCA analysis data showed that grain yield (Yp) was associated with MP, GMP, STI and MRP (Fig. 1). The same indices correlated with (Ys) as well, which can be objectively evaluated by seven more indices as follows:

HM, MSTI, SNPI, YI, AR, PCI and RSI. This was also fully confirmed by the right part of Figure 1, which reflects the ordering of the indices by cluster analysis. Therefore, evaluation of the variety as high yield and drought tolerance can be done by using any one of the indices: MP, GMP, STI, MSTI and MRP.

Cluster analysis of the 27 PRs showed a configuration different from the first data set (Fig. 2). The yield ranks under the two sets of conditions were in one cluster together with nine other indices. Stress resistance could be successfully measured by each of them plus the indices TOL, SSI, YSI and RSI, which were in one cluster. Grain yields under favourable conditions (Yp) again have a high positive correlation with the indices MP, GMP, STI and MRP (PCA, left), while relative to the rest the correlations approach implausibly low positive values (the angle between their vectors > 45°). With this data

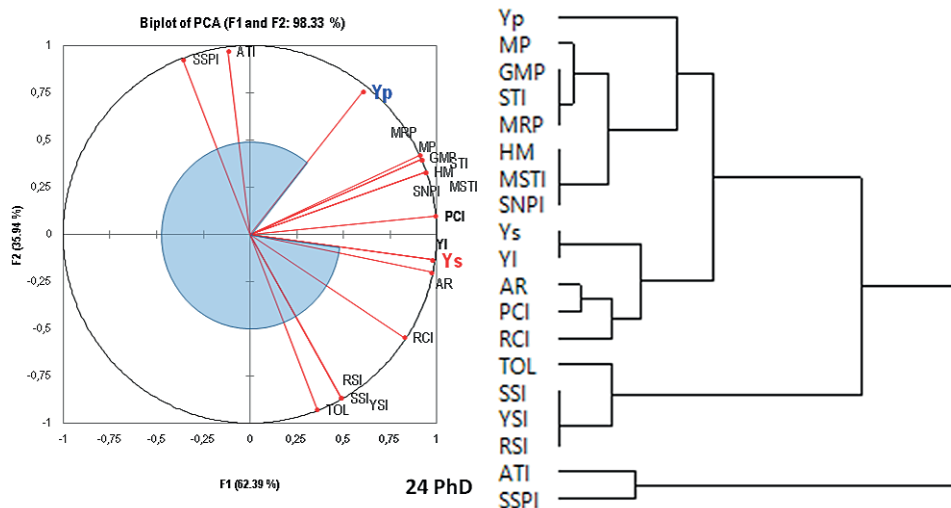


Fig. 1. PhD database: Spearman correlations between indices by principal component analysis (left) and cluster analysis (right)
 Source: Authors' own elaboration

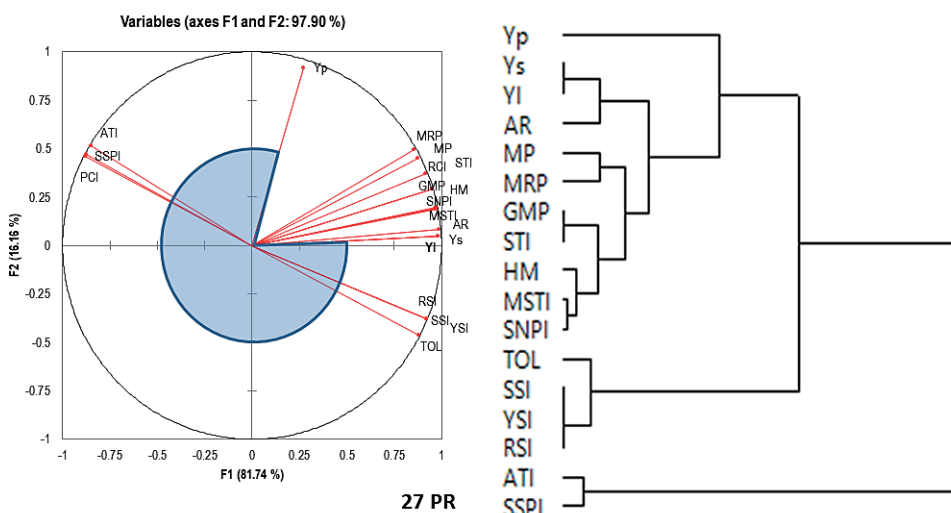


Fig. 2. 27 PR database: Spearman correlations between indices by principal component analysis (left) and cluster analysis (right)
 Source: Authors' own elaboration

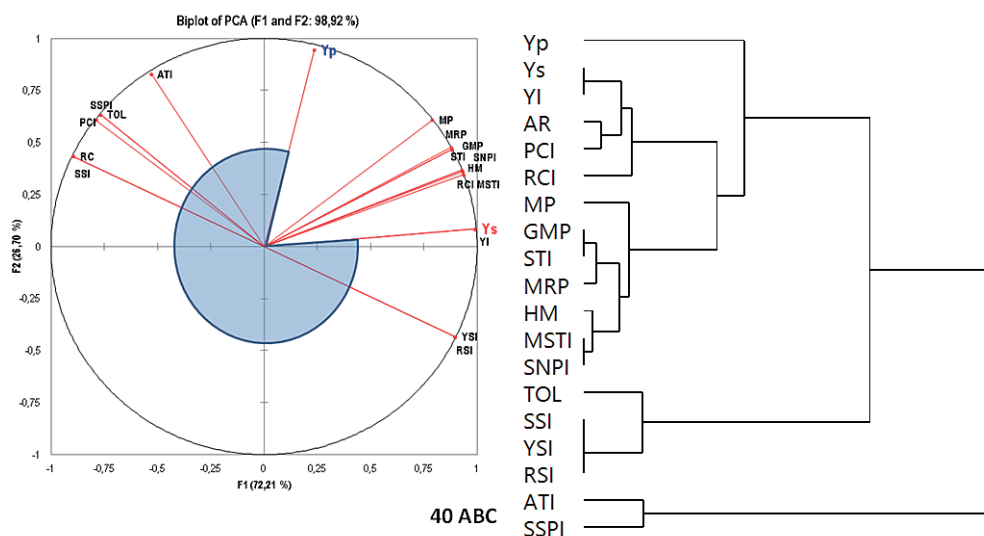


Fig. 3. 40 ABC database: Spearman correlations between indices by principal component analysis (left) and cluster analysis (right)

Source: Authors' own elaboration

set, the variety can be successfully evaluated by the MP, GMP, STI and MRP indices, which have a sufficiently strong relationship with yield under both types of growing conditions.

In database 40 ABC, the location of the studied indices was analogous to the previous database (Fig. 3). The configuration of the PCA index vectors (left), as well as the arrangement of the clusters on the right of the same figure were completely similar. The vectors of the MP, GMP, STI, MRP and MSTI indices were located almost equidistant from that of the (Yp) and (Ys) vectors, making them fully applicable for evaluation in this group of cultivars as well. The spatial configuration of the index vectors in both types of statistical analysis identified the indices MP, GMP, STI, MSTI and MRP, which similarly evaluated the cultivar by its grain yield under the two types of conditions studied.

The next step in the study was to present the rank correlations between the yield under favourable and stressful conditions and the values, averaged from the three datasets of each studied index (Fig. 4). The data fully confirmed the thesis that tolerance to stress can be assessed by almost any of the indices studied. Only the ATI and SSPI indices showed a relatively weaker correlation than all the others. With regard to mining under favourable conditions, the situation was radically different. Most of the indices showed a low or even negative correlation and only a few of the ones already mentioned (GMP, STI and MSTI (SNPI) are applicable in this group.

In this situation to fully evaluate the variety, it was necessary to report its grain yield levels under the contrasting conditions of the environment (Yp and Ys). When the variety is compared with others in the group, there is a need for different levels of compromise between them. They could be conditionally divided into the following principal groups:

1). sufficiently drought tolerant cultivars with sufficiently high grain yield (above group average) – GMP, STI and MSTI were applicable; 2). Stress-tolerant cultivars with relatively high grain yield (similar to the average for the group) – the most efficient were HM, MRP and SNPI; 3). Highly stress tolerant varieties with grain yield lower than the group average – applicable were YI, AR, PCI and RSI.

Finally, in order to illustrate the effectiveness of the application of the identified and selected as the most informa-

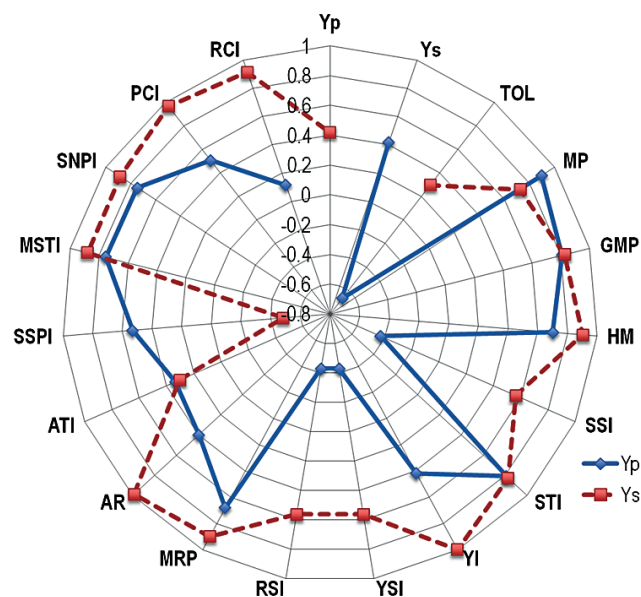


Fig. 4. Mean data for Spearman correlations between grain yield ranks and stress tolerance indices ranks

Source: Authors' own elaboration

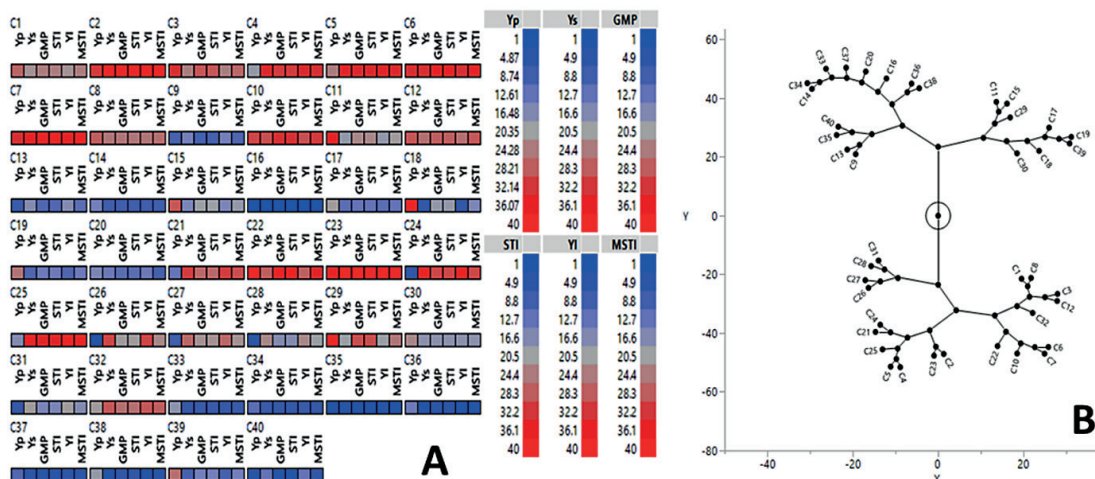


Fig. 5. Visual comparison of cultivars by: A- selected informative indices, the correlation of which to both types of conditions is high and B- grouping of cultivars, according to a complete combination of all investigated indices, C1, C2...C39, C40-identification of the varieties of the group.

Source: Authors' own elaboration

tive indicators, the group of varieties of 40 ABC, due to the largest number of varieties, was evaluated compared to the other databases (Fig. 5).

By direct comparison between the evaluations of the variety along the entire range of indicators (B) and those showing high performance (A) (GMP, STI and MSTI), the studied varieties were successfully separated into analogous groups similar to those already mentioned. YI was also added to the group of selected indices because it has an almost 100% correlation with high stress tolerance. The two ways of representing varieties by cluster analysis define the same varieties for the respective groups: *I*). the high-yielding stressed and non-stressed cultivars (their yield ranks and indices are mostly coloured in blue (Fig. 5A) were twelve: C9, C13, C14, C16, C20, C33, C34, C35, C36, C37, C38 and C40. These same varieties in Fig. 5B were located in two clusters located in the upper left corner. The most valuable of them are C9, C13, C16 and C40 in both parts of Fig.5; *II*). Varieties with high yield under favourable and medium high yield under stress are C21, C24, C26, C27, C28 and C31; *III*). Highly stress-resistant varieties with relatively low grain yield under favourable growing conditions: C11, C15, C18, C19 and C39.

Discussion

For the climatic zone in which Bulgaria is located, there are both autumn (X–XII) spring (IV–VI), and sometimes drought periods during almost the entire growing season. These negatively affect grain yield, to varying degrees from season to season, with the difference typically being around

30–40% (Tsenov et al., 2008; Boyadjieva and Andonov, 2010). This strong variation in yield is a reason to work actively to achieve higher drought tolerance to preserve, to some extent, the high productive potential of Bulgarian wheat varieties (Tsenov et al., 2022a), even under stress conditions in some of the growing seasons or locations. Significant differences between grain yields in the favourable conditions of Dobrich location compared to the stress conditions at the other locations ranged from 27–35%. Similar differences in field experimental conditions were reported by Zhang et al. (2018), when summarizing information from about 60 wheat-related and 55 rice-related scientific publications.

The grain yields in the surveyed stations in Straldzha, Radnevo and Plovdiv were significantly lower than those in Dobrich (-28% ÷ -35%). They are due to the strong interaction between the conditions of the location and the season, in terms of the amounts of rainfall and active temperatures, which in certain combinations cause a decrease/increase in grain yield (Tsenov et al., 2022b). The strong interaction of genotype and location conditions cause these significant changes in grain yield, by which each genotype could be compared with the others in the group. These data are sufficient justification to adopt these particular locations as test sites for the eventual objective assessment of stress tolerance level. The application of these indices in these conditions provides valuable data have enriched breeding information in relation to efforts to combine high productivity and stress tolerance.

Drought tolerance of wheat in the broad sense means that the variety “loses” as little of its productive potential as pos-

sible in the presence of abiotic stress. In this aspect, the evaluation of group of varieties is interesting because it would rank those of them that most strongly meet these conditions. Developing cultivars to maximize their productive potential is a primary task of breeding in wheat (Tsenov et al., 2015; Reynolds and Braun, 2022). When this is done under favourable growing conditions, stress tolerance is a quality that the cultivar would not exhibit, even if it possessed it without provocative stress conditions. The opposite is the situation when cultivars are purposefully developed with high tolerance to specific environmental stress conditions, and their potential productivity is little known due to lack of sufficiently favourable conditions for evaluation (Boyadjieva and Andonov, 2010; Sharma et al., 2023). Ali and El-Sadek (2016) are of the opinion that tolerance in wheat should be measured at locations where moderate drought is present. According to Fischer and Maurer (1978), stress grading classification, in our case there was similar “mild” drought in two of the databases and “moderate” in 40 ABC dataset. On the other hand, Mohammadi (2019) reported that under varying degrees of drought, the indices give a correct estimate of genotype irrespective of the level of stress in a given season. The indices are STI, GMP, MP, SSI, TOL, whose average rank they used as a new index under the name multiple scoring index (MSI). In this study, the first three of these indices (STI, GMP, MP), can correctly estimate cultivar yield under both sets of conditions, while the other two (SSI, TOL) are indices only for highly tolerant genotypes. Ivanova et al. (2011) and Tsenov et al. (2017) found the indices STI, GMP, MP, could be used to estimate under contrasting conditions of yield formation in different seasons. The performance of the three indices for evaluation is high, which is a confirmation of the results of other related studies (Anwaar et al., 2020; Mittal and Singh, 2021; Fatehi et al., 2022). The indices are STI, GMP, MP, SSI, TOL, whose average rank they used as new index under the name multiple scoring index (MSI). In this study, the first three of these indices (STI, GMP, MP), can correctly estimate cultivar yield under both sets of conditions, while the other two (SSI, TOL) are indices only for highly tolerant genotypes. Ivanova et al. (2011) and Tsenov et al. (2017) found that the indices STI, GMP, MP, could be used to estimate under contrasting conditions of yield formation in different seasons. The performance of the three indices for evaluation is high, which is a confirmation of the results of other related studies (Anwaar et al., 2020; Mittal and Singh, 2021; Fatehi et al., 2022).

Under higher abiotic stress (in this case at 40 ABC), these indices are more indicative for simultaneous yield estimation at (Y_p) and (Y_s). In the (27 PhD) data base where the difference between yields under stress and no stress was smallest,

the effectiveness of the same indices decreased. This is in some sense inconsistent with previous studies (Mohammadi and Geravandi, 2024), in which such doubt was shown to be untenable and could hardly be interpreted in this way.

Despite the small sample of effective indices (GMP, STI, MSTI and YI) against the large number of subjects, the PCA and cluster analysis used showed an unexpectedly large number of samples (12) whose yield plus tolerance combination fit the model pursued by the target. They represent about 30% of the tested, which is an outstanding achievement from a breeding point of view. The most valuable of these, which are distinguished by a compromise between yield and tolerance, are five, accounting for about 12% of the entire group of varieties. At the other pole of the group are also five accessions whose use should be avoided in breeding due to low yield and tolerance levels. The widely used indices TOL, SSI, Yi and YSi should not be applied as they identify only extremely tolerant varieties with proven low productivity.

With differences in environmental conditions causing a natural difference of about 30% in grain yield, some of the known indices have been most effective in identifying the most valuable varieties in given group. Their number on the background of the group studied is small, but is similar to that reported in a number of studies conducted in different combinations of conditions

In this respect, in our opinion, the probability of high productivity being successfully combined with a relatively high level of tolerance depends on the breeding procedure. If wheat breeding is carried out under relatively favorable or controlled (irrigated) conditions, it should be aimed at achieving the maximum possible productivity (Anwaar et al., 2020; Lamba et al., 2023). When cultivars developed in this way are tested under stress conditions, it is inevitable to identify those cultivars that combine these traits in a compromise manner. Because wheat is grown annually in regions where drought is potentially likely during the growing season (Tsenov et al., 2008; Boyadjieva and Andonov, 2010), gathering additional information on the tolerance of new varieties is imperative. Therefore, the evaluation of varieties using the appropriate indices should be conducted at test sites, such as those described in the study, so they can be successfully located for production in different regions under different conditions.

Conclusions

The majority of the 17 evaluation indices analyzed could successfully differentiate cultivars under stressful environmental conditions by grain yield, except for two of them, the Abiotic Tolerance Index (ATI) and the Stress Susceptibility Percentage Index (SSPI), whose values were associated with

low levels of tolerance.

The application of only one of the GMP, STI and MSTI indices alone or in a group provides accurate information about the variety in terms of its yield under both favourable and stressful growing conditions. Each of these indices is effective without regard to differences in grain yield formation conditions in wheat.

The set of indices for genotype evaluation depends on the degree of variation between stressed and unstressed conditions. For selection effects without regard to the specific varieties in the group, it is imperative to use a larger number of indices in order to establish exactly which indices are applicable to the specific conditions and group of varieties.

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