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Assessing Tomato Drought Tolerance Based on Selection Indices

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Summary: This study was aimed to assess drought tolerance in twelve tomato populations collected in the territory of Serbia and to investigate relationships and repeatability among sixteen drought tolerance indices. Drought tolerance was estimated at the stage of intensive vegetative growth, on the basis of dry weight yield determined at optimal and limited irrigation (volumetric soil water content of 35.0 and 20.9%, respectively). The trial was set in pots placed in the greenhouse. Significant differences were found among populations in terms of all considered parameters; populations G125, G105 and G104 performed well in both irrigation regimes. High repeatability was found between the selection indices TOL and SSPI, STI and GMP, DWdr and YI, and among SI, SSI, RDI, SDI and RD. Principal component analysis allows simultaneous evaluation of populations and interpretation of interrelationships among the indices; it may be recommended as a method of choice for data analysis in further studies on drought tolerance in tomato.
Key words: drought tolerance, *Lycopersicon esculentum* Mill., principal component analysis, selection indices, tomatoes, vegetative growth

Introduction

Tomato is one of the most consumed and the most economically important vegetables, occupying approximately 20,000 ha in Serbia. Varieties and hybrids of local origin (Institute of Field and Vegetable Crops in Novi Sad and Institute for Vegetable Crops in Smederevska Palanka) are of good quality and yield potential; however, the registered average yield from commercial production of about 9.5 t/ha is low, mainly due to limited investments in growing technology (Takač et al. 2007, Zdravković et al. 2010, Glogovac et al. 2012, Stat. Yearb. Serb. 2012).

Drought is considered as one of the major constraints limiting agricultural production, including the production of tomato. This vegetable has considerably high water demands at all developmental stages, but on the other hand, areas of irrigated tomato in our country are limited. Therefore, breeding tomato for drought tolerance would be an appropriate approach for solving this problem. Since modern cultivars and hybrids are mainly drought sensitive, a useful strategy may be to introduce in breeding programs the material collected and described as adaptive in the target areas, such as domestic, local populations (Foolad 2007, Glogovac & Takač 2010, Maksimović et al. 2012, Zdravković et al. 2013).

Besides the starting material, it is of great importance to choose the selection criteria applied to distinguish desirable genotypes. Drought tolerance indices calculated on the basis of plant performance (in terms of yield, dry matter yield, and/or other quantitative traits) in stressful and non-stressful environments are widely used to assess the response to limited irrigation. However, numerous indices that have been proposed by different authors (e.g. Fischer & Maurer 1978, Fernandez 1992, Moosavi et al. 2008) somewhat

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complicate the selection by classifying the genotypes in different manners.

This study was conducted to assess drought tolerance in twelve tomato populations collected in Serbia, to investigate interrelationships and repeatability among sixteen widely used drought tolerance indices, and therefore to propose the appropriate method for the analysis of such data.

Materials and Methods

Twelve tomatoes (*Lycopersicon esculentum* Mill.) have been chosen for this study due to their morphological, chemical and agronomic traits that could be useful in breeding cultivars and hybrids of high yield and quality. The accessions (G104, G105, G109, G112, G114, G115, G118, G120, G122, G123, G125, and G138) are populations collected in the territory of the Republic of Serbia and they are a part of the collection maintained at the Institute for Vegetable Crops in Smederevska Palanka, where the experiment was conducted.

The greenhouse pot experiment was set in complete randomized blocks with three replications. The replications included 15 plants. After the initial growth that took place in optimal conditions, tomato seedlings were transplanted into pots containing commercial compost (600 cm^3 per pot, Biolan C1-B, Finland) and irrigated daily to full pot holding capacity (volumetric soil water content 35.0%) for ten days; then the half of the plants remained at the same irrigation regime (control) and the other half was subjected to drought treatment (soil water content 20.9%). Time domain refractometer probe (TRASE, Soil Moisture Equipment Corp., USA) was used for soil water content measurements. Ten days after, when the plants were still in the vegetative growth stage, the experiment was stopped and plant dry weight yield was determined by drying in oven at 80°C to constant weight. The relations between dry weights measured at optimal irrigation (DWirr) and drought (DWdr) served as the basis for calculating selection indices and assessing tomato drought tolerance. The indices were calculated as follows, with $\overline{DWirr}\overline{DWirr}$ and $\overline{DWdr}$ $\overline{DWdr}$ representing the mean DW of populations evaluated at irrigation and drought, respectively:

1. Stress susceptibility index: $SSI = [1-(DWdr\ /\ DWirr)]/[1-(\overline{DWdr}/\overline{DWirr})]$ $SSI = [1-(DWdr\ /\ DWirr)]/[1-(\overline{DWdr}/\overline{DWirr})]$ (Fischer & Maurer 1978)
2. Relative drought index: $RDI = (DWdr/DWirr)/(\overline{DWdr}/\overline{DWirr})$ $RDI = (DWdr/DWirr)/(\overline{DWdr}/\overline{DWirr})$ (Fischer & Wood 1979)
3. Mean productivity: $MP = (DWirr + DWdr)/2MP = (DWirr + DWdr)/2$ (Rosielle & Hamblin 1981)
4. Stress tolerance: $TOL = DWirr - DWdrTOL = DWirr - DWdr$ (Rosielle & Hamblin 1981)
5. Stability index: $SI = DWdr/DWirrSI = DWdr/DWirr$ (Bouslama & Schapaugh 1984)
6. Dry weight yield index: $YI = DWdr/\overline{DWdr}YI = DWdr/\overline{DWdr}$ (Lin et al. 1986)
7. Superiority index: $Pi = \sum_{j=1}^{n}(Xij - Mj)^2/2nPi = \sum_{j=1}^{n}(Xij - Mj)^2/2n$, with *n* representing the number of environments, *Xij* grain yield of i^{th} accession in the j^{th} environment and *Mj* the yield of the accession with maximum yield at environment *j*. (Lin & Binns 1988)
8. Stress tolerance index: $STI = (DWdr \times DWirr)/\overline{DWirr}^2STI = (DWdr \times DWirr)/\overline{DWirr}^2$ (Fernandez 1992)
9. Geometric mean productivity: $GMP = \sqrt{(DWirr \times DWdr)}GMP = \sqrt{(DWirr \times DWdr)}$ (Fernandez 1992)
10. Harmonic mean: $HM = (2 \times DWirr \times DWdr)/(DWirr + DWdr)$ $HM = (2 \times DWirr \times DWdr)/(DWirr + DWdr)$ (Schneider et al. 1997)
11. Drought resistance index: $DI = [DWdr \times (DWdr/DWirr)]/\overline{DWdr}$ $DI = [DWdr \times (DWdr/DWirr)]/\overline{DWdr}$ (Lan 1998)
12. Modified stress tolerance index: $k1STI = DWirr^2/\overline{DWirr}^2k1STI = DWirr^2/\overline{DWirr}^2$ and $k2STI = DWdr^2/\overline{DWdr}^2k2STI = DWdr^2/\overline{DWdr}^2$ (Farshadfar & Sutka 2002)
13. Abiotictoleranceindex: $ATI = [(DWirr - DWdr)/(\overline{DWirr}/\overline{DWdr})] \times [\sqrt{DWirr \times DWdr}]$ $ATI = [(DWirr - DWdr)/(\overline{DWirr}/\overline{DWdr})] \times [\sqrt{DWirr \times DWdr}]$ (Moosavi et al. 2008)
14. Stress susceptibility percentage index: $SSPI = [(DWirr - DWdr)/2(\overline{DWirr})] \times 100$ $SSPI = [(DWirr - DWdr)/2(\overline{DWirr})] \times 100$ (Moosavi et al. 2008)
15. Sensitivity drought index: $SDI = (DWirr - DWdr)/DWirrSDI = (DWirr - DWdr)/DWirr$ (Farshadfar & Javadinia 2011)
16. Relative decrease: $RD = 100 - [(DWdr \times 100)/DWirr]$

Data were initially processed by analysis of variance. The ranks were assigned to populations for each selection index and nonparametric Spearman's coefficients of rank correlation were calculated. The relationships among the indices and performance of the individual populations were studied by principal component (biplot) analysis, while three-dimensional plots were used for distinguishing the populations with favorable performance at both irrigation and drought conditions. All calculations and drawings were performed using Statistica 12 software package (StatSoft, Tulsa, OK, USA; University of Novi Sad License).

Results and Discussion

Tomato seedlings dry weights differed significantly among the analyzed populations and between the two irrigation regimes, implying the possibility for breeding cultivars with enhanced tolerance to drought occurring at the stage of intensive vegetative growth. The most important source of variation were the irrigation treatments (61.2%), while populations and population × treatment interaction accounted for 25.7 and 12.9% of total sum of squares, respectively (data not shown). Similar results have been reported by Ilker et al. (2011) and Farshadfar et al. (2012b) for the effects of drought on field grown bread wheat.

Plant dry weights measured at optimal irrigation and drought, together with the estimated selection indices and the corresponding ranks assigned to the accessions are given in Table 1. In addition to drought selection indices, the relative decrease in dry weight (RD), as a widely used parameter for describing yield or dry weight response to various abiotic stresses (e.g. Magán et al. 2008), has been calculated. Concerning RD, tomato seedlings grown in drought had on average 64.4% lower dry weights when compared to those from optimal irrigation, indicating considerably high stress intensity.

Populations differed significantly in terms of all studied indices. As for their ranking, in several cases the order was the same (e.g. SSI, SDI and RD; RDI and SI; STI and GMP); therefore the highly significant repeatability among such indices implies that any of them can be used individually in further studies. Similar relations among those indices have been reported by Anwar et al. (2011) and Farshadfar et al. (2012a). However, the ranking was different in some other cases, complicating the selection of drought tolerant populations. For example, populations G138, G104 and G109 were the most tolerant according to RDI and SI, STI and GMP distinguished populations G125, G105 and G104 and Pi populations G115, G138 and G112. This was somewhat expected since the indices are based on mathematical relations between plant dry weight determined at the two irrigation regimes, in some cases taking into account one of the environments to a greater extent.

With the intent to examine the relationships among the selection indices and plant dry weight under irrigation and drought, Spearman's coefficients of rank correlation have been estimated (Table 2). MP, TOL, Pi, STI, GMP, k_1STI, ATI and SSPI correlated to dry weight of irrigated, while SSI, RDI, SI, YI, STI, GMP, HM, DI, k_2STI, SDI and RD correlated to dry weight of plants exposed to drought. Thus, only STI and GPM (which provided the same ranking of populations) correlated to dry weight measured under both conditions, while other indices may be recommended for evaluating accessions under individual irrigation regimes. Lack of significant correlation between dry weight of plants grown under optimal and limited irrigation ($r = 0.22$) implies the variability among the studied tomato populations and confirms that accessions with high dry weight under optimal irrigation are not necessarily drought tolerant.

Stress tolerance index (STI) has been proposed by Fernandez (1992) as a useful criterion for distinguishing accessions into groups of different performance at optimal and limited irrigation. Plant dry weights from the two irrigation regimes and STI plotted on three-dimensional graph allow the division of the x-y area into four groups, marked as A, B, C and D (Figure 1). Accessions belonging to group A are the desirable ones, characterized by high dry weight at both optimal and limited irrigation (G125 and G105). G114 was the only population in group B (high dry weight at irrigation, low in drought), while group C (low dry weight at irrigation, high in drought) consisted of G104, G138 and G109. The remaining six populations (G112, G120, G118, G123, G122, and G115) fell into group D (poor performance at both irrigation regimes) and they are not the appropriate starting material for breeding tomato for drought tolerance. However, although STI (and GMP) were the only indices in our study correlating significantly to dry weight measured at both irrigation regimes, there is still a possibility that the selection based on more indices would be more effective (Talebi et al. 2009). Besides for

Table 1. Mean values and the corresponding ranks of drought stress selection indices (SSI – RD) based on tomato seedling's dry weight determined at optimal irrigation (DWirr, g) and drought (DWdr, g)

Population	DWirr	DWdr	SSI	RDI	MP	TOL	SI	YI	Pi	STI	GMP	HM	DI	k_1STI	k_2STI	ATI	SSPI	SDI	RD
G104	145.5	68.9	0.794	1.407	107.2	76.6	0.474	1.310	4752.2	0.411	100.1	93.5	0.621	0.357	0.711	2579.5	24.5	0.526	52.6
G105	206.5	69.7	0.999	1.002	138.1	136.8	0.337	1.324	1548.2	0.589	119.9	104.2	0.447	1.031	1.040	5523.2	43.8	0.663	66.3
G109	125.2	55.9	0.834	1.327	90.6	69.3	0.447	1.063	6434.8	0.287	83.7	77.3	0.475	0.185	0.325	1953.3	22.2	0.553	55.3
G112	109.4	47.1	0.857	1.281	78.3	62.2	0.431	0.896	7926.8	0.211	71.8	65.8	0.387	0.104	0.172	1505.3	19.9	0.569	56.9
G114	207.4	32.5	1.271	0.465	120.0	175.0	0.156	0.617	2316.2	0.276	82.1	56.1	0.097	0.486	0.106	4832.5	56.0	0.844	84.4
G115	99.5	20.6	1.196	0.613	60.0	78.9	0.206	0.391	9600.0	0.084	45.2	34.1	0.081	0.034	0.013	1201.6	25.2	0.794	79.4
G118	160.2	41.0	1.121	0.761	100.6	119.2	0.256	0.780	4361.2	0.269	81.1	65.3	0.200	0.283	0.165	3250.5	38.1	0.744	74.4
G120	116.3	42.3	0.960	1.079	79.3	74.0	0.363	0.803	7461.5	0.201	70.1	62.0	0.293	0.112	0.132	1746.0	23.7	0.637	63.7
G122	146.5	33.6	1.162	0.681	90.1	112.8	0.229	0.639	5453.6	0.202	70.1	54.6	0.148	0.179	0.086	2662.4	36.1	0.771	77.1
G123	122.2	35.1	1.076	0.851	78.6	87.1	0.286	0.667	7189.5	0.176	65.4	54.5	0.192	0.108	0.081	1920.0	27.9	0.714	71.4
G125	277.1	91.2	1.011	0.978	184.2	185.9	0.329	1.733	11.0	1.034	159.0	137.2	0.571	3.253	3.120	9944.9	59.5	0.671	67.1
G138	89.6	67.7	0.368	2.245	78.7	21.9	0.756	1.287	9329.8	0.248	77.9	77.1	0.972	0.082	0.413	576.1	7.0	0.244	24.4
Mean	150.5	50.5	0.971	1.057	100.5	100.0	0.356	0.959	5532.1	0.332	85.5	73.5	0.374	0.518	0.530	3141.3	32.0	0.644	64.4
LSD 0.05	6.9	5.4	0.042	0.082	6.0	3.3	0.028	0.103	600.4	0.050	6.7	7.0	0.057	0.149	0.237	292.6	1.1	0.028	2.8
LDS 0.01	9.3	7.3	0.056	0.111	8.1	4.5	0.037	0.139	813.6	0.068	9.0	9.5	0.077	0.202	0.321	396.5	1.4	0.037	3.8
Ranks																			
G104	6	3	11	2	4	8	2	3	8	3	3	3	2	4	3	6	8	11	11
G105	3	2	7	6	2	3	6	2	11	2	2	2	5	2	2	2	3	7	7
G109	7	5	10	3	6	10	3	5	6	4	4	4	4	6	5	7	10	10	10
G112	10	6	9	4	11	11	4	6	3	8	8	6	6	10	6	10	11	9	9
G114	2	11	1	12	3	2	12	11	10	5	5	9	11	3	9	3	2	1	1
G115	11	12	2	11	12	7	11	12	1	12	12	12	12	12	12	11	7	2	2
G118	4	8	4	9	5	4	9	8	9	6	6	7	8	5	7	4	4	4	4
G120	9	7	8	5	8	9	5	7	4	10	10	8	7	8	8	9	9	8	8
G122	5	10	3	10	7	5	10	10	7	9	9	10	10	7	10	5	5	3	3
G123	8	9	5	8	10	6	8	9	5	11	11	11	9	9	11	8	6	5	5
G125	1	1	6	7	1	1	7	1	12	1	1	1	3	1	1	1	1	6	6
G138	12	4	12	1	9	12	1	4	2	7	7	5	1	11	4	12	12	12	12

Table 2. Spearman's coefficients of rank correlation among drought stress selection indices (SSI – RD) and tomato seedling's dry weight determined at optimal irrigation (DWirr) and drought (DWdr)

	DWdr	SSI	RDI	MP	TOL	SI	YI	Pi	STI	GMP	HM	DI	k_1STI	k_2STI	ATI	SSPI	SDI	RD
DWirr	0.22	-0.40	-0.40	0.90**	-0.88**	-0.40	0.22	-0.98**	0.69*	0.69*	0.38	-0.04	0.94**	0.34	-0.99**	-0.88**	-0.40	-0.40
DWdr		0.73**	0.73**	0.52	0.05	0.73**	1.00**	-0.39	0.76**	0.76**	0.96**	0.92**	0.48	0.97**	-0.29	0.05	0.73**	0.73**
SSI			1.00**	-0.04	0.70*	1.00**	0.73**	0.23	0.30	0.30	0.63*	0.90**	-0.11	0.64*	0.36	0.70*	1.00**	1.00**
RDI				-0.04	0.70*	1.00**	0.73**	0.23	0.30	0.30	0.63*	0.89**	-0.11	0.64*	0.36	0.70*	1.00**	1.00**
MP					-0.69*	-0.04	0.52	-0.95**	0.89**	0.89**	0.66*	0.32	0.98**	0.64*	-0.91**	-0.69*	-0.04	-0.04
TOL						0.70*	0.05	0.82**	-0.38	-0.38	-0.06	0.35	-0.73**	-0.04	0.87**	1.00**	0.70*	0.70*
SI							0.73**	0.23	0.30	0.30	0.63*	0.90**	-0.11	0.64*	0.36	0.70*	1.00**	1.00**
YI								-0.39	0.76**	0.76**	0.96**	0.92**	0.48	0.97**	-0.29	0.05	0.73**	0.73**
Pi									-0.79**	-0.79**	-0.52	-0.13	-0.98**	-0.50	0.99**	0.82**	0.23	0.23
STI										1.00**	0.90**	0.62*	0.85**	0.87**	-0.71**	-0.38	0.30	0.30
GMP											0.90**	0.62*	0.85**	0.87**	-0.71**	-0.38	0.30	0.30
HM												0.86**	0.62*	0.99**	-0.43	-0.06	0.63*	0.63*
DI													0.23	0.88**	0.00	0.35	0.90**	0.90**
k_1STI														0.58*	-0.95**	-0.73**	-0.11	-0.11
k_2STI															-0.39	-0.04	0.64*	0.64*
ATI																0.87**	0.36	0.36
SSPI																	0.70*	0.70*
SDI																		1.00**

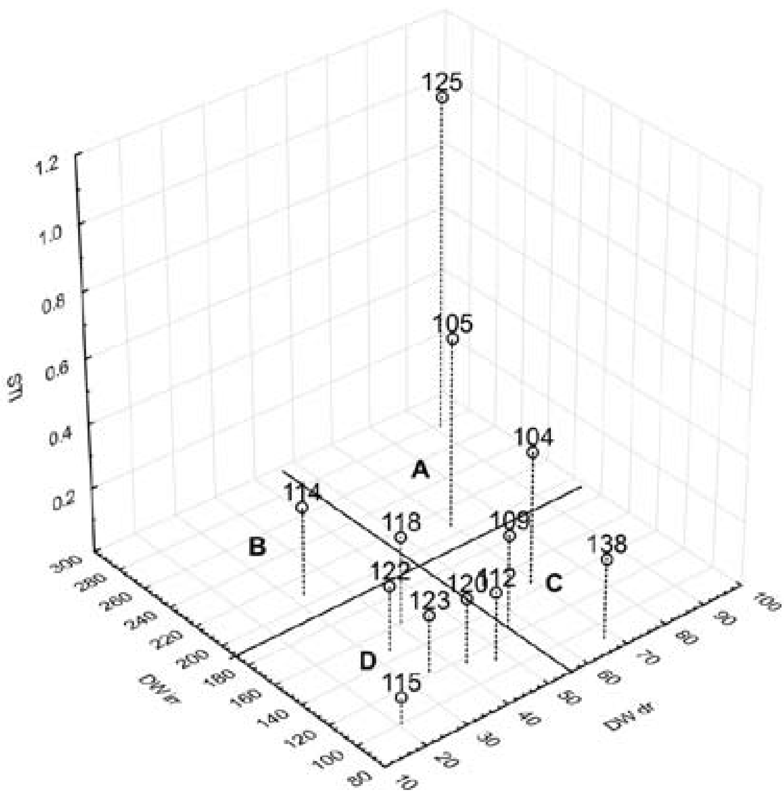

Figure 1. Three-dimensional plot of tomato seedling's dry weight at drought (DWdr), optimal irrigation (DWirr) and stress tolerance index (STI)

the two indices, correlations with wheat and oat yield determined at both drought stress and non-stress conditions have been reported for SI, SSI, MP, HM, TOL, YI and Pi (Akçura & Çeri 2011, Akçura et al. 2011), probably related to differences in stress intensity and experimental design, as well as to plant species and genotypes within the species included in the studies.

In order to further investigate the interrelationships and repeatability among drought selection indices, as well as to distinguish tolerant populations on the basis of several indices, principal component (PC) analysis has been performed and the corresponding biplot has been drawn (Figure 2). PC1 and PC2 accounted for 66.5% of the total variation. The cosine of the angle between the index vectors represents their approximate positive (acute angles) or negative (obtuse angles) correlation. Overlapping index vectors refer to correlation coefficient of 1 and an identical ranking of accessions. As depicted in biplot and in accordance to Spearman's coefficients of rank correlation, high repeatability was found between TOL and SSPI, STI and GMP, DWdr and YI, and among SI, SSI, RDI, SDI and RD. Thus, instead of these eleven, calculating four indices would be sufficient for further studies. In addition, considering both axes simultaneously, three groups of associated indices have been identified: one consisting of Pi only, the second consisting of SI, SSI, RDI, SDI, RD and DI, while all the remaining indices were classified into the third group. Since DWirr and DWdr also fell into the third group, the PC1 dimension can be associated with good performance at both optimal and limited irrigation. PC2 explained 29.1% of the variance and it was positively associated with SI, SSI, RDI, SDI, RD and DI. Therefore, G125, G105 and G104 characterized by high and positive PC1 and low PC2 scores are distinguished as tomato populations performing well in both irrigation regimes (Fernandez's group A). Vice versa, populations with high PC2 and low PC1 (G115, G123, G120, G122, and G118) performed poorly in both stressful and non-stressful conditions (D), while G109, G138 and G112 corresponded to Fernandez's group C, and G114 to group B.

In our study, principal component analysis provided grouping of tomato populations that is similar to grouping on the basis of three-

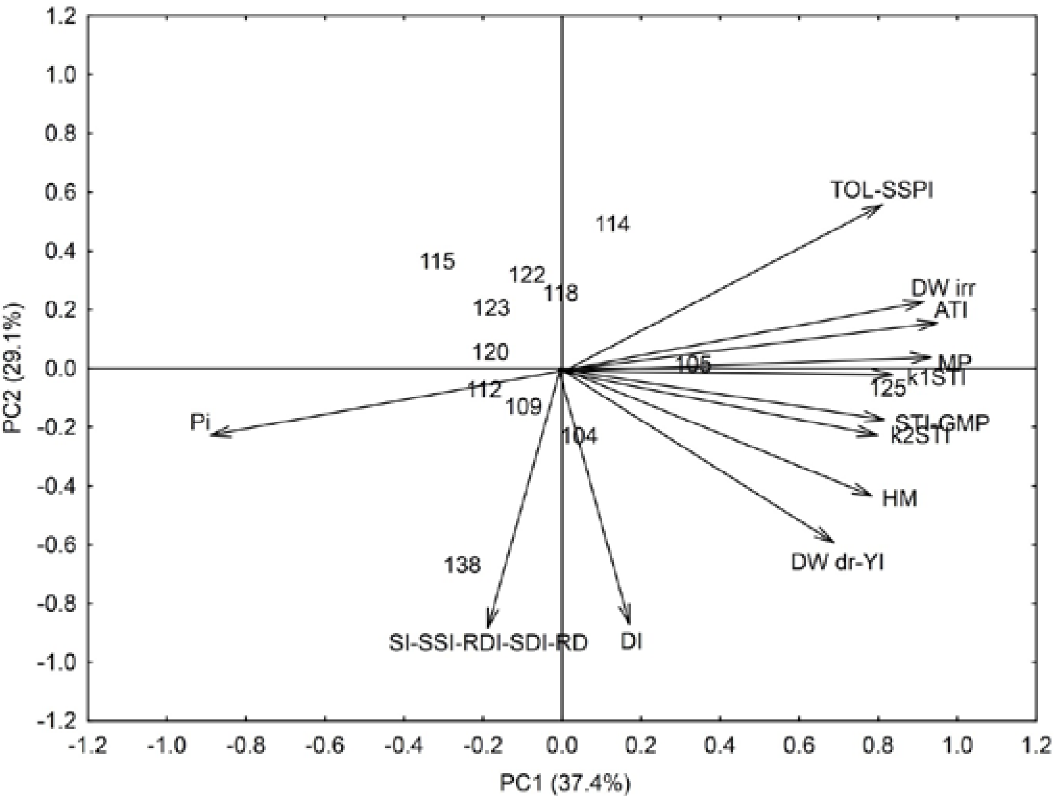

Figure 2. Biplot based on the first two principal component axes for twelve tomato populations and drought tolerance selection indices

dimensional graph including DWirr, DWdr and STI (GMP) only. Since the method allows simultaneous evaluation of the accessions and the interpretation of interrelationships among the indices, it may be recommended as a method of choice for data analysis in further studies on drought tolerance in tomato.

Conclusions

The tomato populations included in this study differed significantly in terms of dry weight yields determined at the stage of intensive vegetative growth in conditions of optimal and limited irrigation, as well as in terms of the calculated drought tolerance indices.

STI and GPM were the only indices that correlated to dry weight measured under both irrigation regimes and the two indices provided the same ranking of the populations. Three-dimensional graphical display of STI, DWirr and DWdr allowed the separation of the accessions with good performance at both irrigation and drought from other accessions.

Grouping of accessions in terms of drought tolerance was similar when carried out via principal component analysis which additionally allowed the interpretation of the relationships among the indices. High repeatability was found between TOL and SSPI, STI and GMP, DWdr and YI, and among SI, SSI, RDI, SDI and RD.

Tomato populations performing well in both irrigation regimes were G125, G105 and G104, while G115, G123, G120, G122 and G118 were characterized by low dry weight yields.

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Procena tolerantnosti paradajza na sušu na osnovu selekcionih indeksa

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Izvod: Ogled je postavljen sa ciljem procene tolerantnosti na sušu dvanaest populacija paradajza prikupljenih na teritoriji Srbije, kao i sa ciljem ispitivanja šesnaest selekcionih indeksa koji se koriste za tu procenu. Tolerantnost na sušu je utvrđena u fazi intenzivnog vegetativnog rasta, na osnovu prinosa suve materije izmerenog u uslovima optimalne i ograničene obezbeđenosti vodom (zapreminski procenat sadržaja vlage u zemljištu 35,0% odnosno 20,9%). Ogled je postavljen u saksijama smeštenim u staklenik. Konstatovane su značajne razlike među populacijama u pogledu svih izučavanih parametara; za populacije G125, G105 i G104 je utvrđen visok prinos suve materije u oba režima zalivanja. Visok stepen ponovljivosti je zabeležen za TOL i SSPI, STI i GMP, DWdr i YI, kao i između SI, SSI, RDI, SDI i RD. Metod glavnih komponenata je omogućio istovremeno vrednovanje populacija i interpretaciju veza između indeksa. Zato može da se preporuči za analizu podataka u budućim istraživanjima koja se tiču tolerantnosti paradajza na sušu.
Ključne reči: *Lycopersicon esculentum* Mill., metod glavnih komponenata, paradajz, selekcioni indeksi, tolerantnost na sušu, vegetativni rast