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Phenotypic Diversity of Red and White Onion Genetic Resources Collected from Different Countries

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ABSTRACT

The phenotypic diversity within onion populations is very high and occurs mostly due to bulb shape, height and diameter, neck width, weight, dry skin colour, bitterness and dry skin thickness. This study aimed to determine the phenotypic diversity of the genetic resources of red and white onions collected from different countries. Initially, a gene pool of 23 onion genetic resources was established, consisting of 14 red and 9 white onions. As a result of the research, it was determined that the red and white onion genotypes showed a high level of phenotypic diversity in terms of morphological traits. Cluster and principal component analysis (PCA) were performed to determine the relationships among the onion genotypes. As a result of the cluster analysis based on 31 variables, three groups and five subgroups were identified in the red onion genetic resources and two groups and four subgroups were clustered in the white onion genetic resources. A dendrogram was performed to evaluate the morphological similarities between the red and white onion genotypes. In the red onion genotypes, seven PC axes with an eigen value greater than 1 explained 90.2% of the total variation within the PCA. The total variation in white onion genotypes was found to be 96.4%. These results showed that the genetic variability was very high between the red and white onion genotypes. The results obtained will help onion breeders to develop high-quality, new onion varieties in the future.

Keywords**:** *Allium cepa,* genetic resources, diversity, multivariate analysis

Introduction

Onions are consumed for their bulbs and fresh green leaves. They are an appetizing vegetable species which can used in various ways, including raw in salads, cooked in meals, dried and used as spice powder in processed foods such as chips and cracker, and chopped and frozen in mass-produced food stuffs (Gökçe 2022). Onions are grown in all regions of the world except Antarctica. The global dry onion production in 2020 was approximately 104.554.458 tons, while the production of green onions was 4.452.728 tons (FAO 2022). The major onion producing countries are China, India, the USA, Egypt, Iran, and Türkiye.

The onion (*Allium cepa* var. *cepa* L.) was one of the first agricultural plants cultivated by human beings. It is a member of the Amaryllidaceae family within the *Allium* genus. There are more than 1000 species in this genus (Jones and Mann 1963; Gökçe 2011). It has been stated in the literature that 150 of these species grow naturally in Türkiye (Gökçe 2001). Edible onions and closely related species (shallot, garlic, leek, chives, Chinese onion) are part of the subfamily Allioideae (Costa et al. 2020). The gene centres of the onion are considered to be Afghanistan, Pakistan, Tajikistan, Iran, India, China, Uzbekistan, Turkmenistan and Türkiye (Karaağaç and Balkaya 2017; Bağcı et al. 2021; Gökçe 2022).

Plant genetic resources are very important in helping them adapt to the different ecologies in which they are grown, their resistance to diseases and pests,

and because they may have desirable characteristics that can be used in breeding programs (Balkaya and Yanmaz 2001; Karaağaç and Balkaya 2017). Using the existing genetic and phenotypic diversity, breeders have achieved significant success in the selection or development of new varieties with the desired characteristics in terms of adaptation, yield, quality, and resistance to diseases and pests in recent years (Taş and Balkaya 2021). The genetic diversity has occurred over time in the countries where onions are grown largely and many different landraces have occurred.

Plant genetic materials adapt to a region over time, and significant changes occur in their genetic structures as a result of environmental conditions. It is thus important to determine the level of morphological variation and phenotypic diversity in breeding programs (Yuguda et al. 2017). Many studies have been carried out by researchers in many different countries in order to collect, characterize and determine the phenotypic diversity levels of onion genetic resources. Mousavizadeh et al. (2006) investigated the morphological and agronomical diversity of Iranian onion landraces. It was determined that there were statistically significant differences between genotypes in terms of traits such as onion yield per plant, onion dry weight, dry matter ratio, bulb diameter, bulb height, shape index, number of leaves and leaf length. In another study, Mallor et al. (2011) studied the morphological and physicochemical characteristics of 86 local onion genetic resources in Spain. Their study determined that there was a high level of morphological variation in terms of bulb weight, shape, hardness, dry matter content and bitterness. Gvozdanovic et al. (2013) investigated the levels of phenotypic diversity in the Serbian onion genetic collection. It was determined that there was a high level of phenotypic diversity in onion genotypes, especially in terms of dry skin colour, the base colour of dry skin, and dry skin thickness traits. Sumalan et al. (2014) investigated phenotypic diversity levels in some local red onion cultivars in the Timiș Region of Romania. They reported that 15 red onion genotypes showed significant differences in terms of morphological characteristics. Sunil et al. (2014) determined phenotypic diversity and genetic variation in onion germplasm collected from different parts of the Indian Peninsular Region. It was determined that there was a high level of variation among genotypes in terms of plant height, number of leaves, leaf length, leaf diameter, bolting, dry matter content and bulb weight. Azimi et al. (2020) conducted a morphological characterization of onion genetic resources collected from Eastern Anatolia and South-eastern Anatolia Regions of Türkiye. As a result of their research, the dry skin colour of onion genotypes was found to be white, reddish and brownish-yellow; the bulb shape was oval or circular and flattened; and the base colour of the skin was white, reddish and yellow. In addition, it was determined that the bulb weight was ranged from 30.06 to 186.2 g and the number of leaves per plant varied between 6.1 and 16.6.

In recent years, it has become a common practice to use multivariate analysis methods in plant breeding programs (Karaağaç and Balkaya 2010). The multifaceted examination of morphological traits allows phenotypic diversity in the initial gene population to be determined. As the characters and the number of samples compared increase, classical statistical methods may be insufficient. The numerical taxonomic classification methods also called multivariate analyses used for the determination of variation and similarities require a sequence of choices, measurements, analyses and interpretations (Tan 2005). Using the data obtained from characterization studies, the existing similarities, differences and groupings are shown through cluster analysis and PCA (Balkaya and Ergün 2008; Balkaya et al. 2010; Karaağaç and Balkaya 2010; Hancı and Gökçe 2016; Kanal and Balkaya 2021). Different researchers have carried out various studies using these analyses to determine phenotypic and genetic diversity in onion populations (Manbachi et al. 2012; Sunil et al. 2014; Hancı and Gökçe 2016; Aryakia et al. 2016; Dangji et al. 2018; Manjunathagowda et al. 2021). This study aimed to determine the level of phenotypic diversity and significant variables in red and white onion genetic resources collected from different regions of the world.

Materials and Methods

This study was conducted between March 2020 and September 2021. In the first stage of the study, 14 red and 9 white onion genetic materials from different countries were obtained from the USDA ARS-National Plant Germplasm System (Table 1).

In order to determine the plant characteristics of the onion genotypes, cultivation experiments were carried out in the Faculty of Agriculture, Ondokuz Mayıs University between April and September 2021. The seeds were sown on 9 April 2021 in the plastic crates filled with a mixture of peat and perlite (v/2:1). The experiment was conducted in a randomized block design with three replications and 10 plants in each replication. All cultural treatments (irrigation, pests and diseases control, fertilization) were carried out regularly during the growing period (Gökçe 2022).

The morphological characterization criteria were used with the modification of the characteristics of the onion by the International Plant Genetic Resources

Research Institute (IPGRI) and the International Union for the Protection of New Varieties of Plants (UPOV) (Table 2, Table 3). The characteristics for the green (fresh) onions were determined in the first week of July, and for the bulb onions between 16 August 2021 and 6 September 2021. The bulbs were harvested when the leaves and the stem of the plant had dried.

The statistical evaluation of the data obtained was carried out in the Numerical Taxonomy Multivariate Analysis System (NTSYS-pc version 2.2; Exeter Software, New York, NY) package program (Rohlf 1993). PCA was applied to determine the amount of morphological variation among the onion genotypes examined, and factor coefficients were obtained indicating the weights of the main components that emerged based on the PC axes, their variance and cumulative variance ratios (Balkaya et al. 2009). PCA was used to determine the degree of characteristic variance between genotypes based on PCA, since one of the factor analysis methods is the reduction of a large number of variables correlated with smaller sets of variables called factors or components. Orthogonal rotation of the factor axes was used to extract factors having eigenvalues > 1 (Mohan et al. 2016). A three-dimensional (3D) PCA was constructed to provide another means of testing the relationships among genotypes using the EIGEN module in the NTSYS. After it was determined that the cumulative variation in the first three axes was of sufficient size, cluster analysis was performed to show the similarities and differences of the genotypes from each other. Row data were standardized and the SIMINT module was used to compute a distance matrix. Then, a distance matrix was used to construct a dendrogram based on the unweighted-pair group method arithmetic average (UPGMA) method in the SAHN (Sequential, agglomerative, hierarchical and nested) clustering method module. In order to see how well a cluster analysis represented the distance matrix, the COPH module was used to transform the tree matrix to a matrix of ultra-metric distances. Finally, the MXCOMP module was used to compare these ultra-metric distances and distance matrix produced for the UPGMA analysis (Huamán and Spooner 2002).

Results and Discussion

Assessment of red and white onion genotypes by principal component analysis

Knowing the existing morphological variations and phenotypic diversity levels in gene pools and applying them to breeding programs are essential elements for increasing success (Balkaya et al. 2010). PCA is performed by displaying the genotype projections on an axis or series of axes that can best represent the relationship between genotypes in vegetable breeding in a multidimensional area (Balkaya et al. 2010; Karaağaç 2013). As a result of the PCA, eight independent axes with eigenvalues greater than 1 were determined in the red onion genotypes. The coefficients of the eigenvalues of the first eight main components varied between 1.3 and 6.8 (Table 4). It has been reported in the literature that principal component axes with eigenvalues greater than 1 are very reliable in PCA analysis (Mohammadi and Prasanna 2003; Özdamar 2004; Balkaya et al. 2010; Kanal and Balkaya 2021). As a result of the analysis, the cumulative variation values of the axes and the total variation rates were also determined. The eight axes were found to represent 90.2% of the total variation (Table 4). Özdamar (2004) reported that in order for factor coefficients to be reliable in PCA, the PC axes should explain 2/3 of the total variation. In the current study, 2/3 of the total variation was more than explained by the first four PC axes (65.3%). Though clear guidelines do not exist to determine the significance of a character coefficient, one rule of thumb is to treat coefficients > 0.3 as having a large enough effect to be considered important (Karaağaç 2006; Taş and Balkaya 2021). The first PC axis accounted for 22.1% of the total variation (Table 4). Traits with a high coefficient were leaf length (-0.43), bulb height (0.32), root disc diameter (0.31), intensity of dry skin colour L (-0.91), intensity of dry skin colour b (-0.87), the position of the maximum diameter of the bulb (0.67), the shape of the bulb's stem end (0.48), time of harvest (0.75), and the base colour of the bulb's dry skin (-0.34). In the second PC axis, which represented 20.5% of the total variation, these traits were the bulb's dry matter content (0.42), the shape of the bulb's root end (0.38), and the thickness of dry skin (-0.85). In the third axis of PC, which represents 13.1% of the total variation, the number of leaves per pseudo stem (-0.93), foliage colour (0.30), intensity of foliage's green colour L (-0.41), leaf diameter (-0.50), and pseudo stem length (-0.47) were the criteria to be considered in the morphological identification. In red onion genotypes, the PC coefficients of bulb weight, diameter and shape characters were found to be low. It is thought that the constricted variation in these characters may have been because the genotypes were selected by the breeder before they were included in the seed gene bank.

As a result of PCA, the total variation was found to be 96.4% among white onion populations (Table 5). According to the analysis, there were seven PC axes with an eigen value greater than 1. The coefficients of the eigenvalues of the seven main components varied between 1.4 and 7.4 (Table 5).

The first PC axis accounted for 25.4% of the total variation (Table 5). Characters with a high coefficient were leaf length (0.69), pseudo stem length (0.30), degree of waxiness (0.36), foliage cranking (0.40), bulb weight (-0.95), bulb height (-0.52), bulb diameter (-0.86), bulb hardness (-0.62), shape of the bulb's root end (0.33), and bulb shape (0.36). In the second PC axis, which represented 21.6% of the total variation, foliage colour (-0.78), leaf diameter (0.33), degree of waxiness (-0.82), dry matter content of bulb (-0.59), intensity of dry skin colour L (0.97), shape of bulb's stem end (-0.54), degustation analysis (0.37) and the maturation time were significant. The third PC axis represented 13.5% of the total variation. In the current study, 2/3 of the total variation was more than explained by the first four PC axes (74.3%).

Traits of commercial importance, such as bulb shape, bulb firmness, and bulb weight and dimensions, for which limited variation was detected in red onions, had a very high variation in the white onion genotypes. These results indicated that white onions are subject to a lower selection severity than red onion genotypes. Many studies have been conducted to determine the levels of morphological variation and phenotypic diversity in onion populations. One study found that the first three principal axes had 83.42% of the total phenotypic diversity in Iranian onion landraces. On the first main axis, bulb dry weight, diameter, bulb dry matter, bulb yield per plant, leaf length and the number of leaves were significant (Mousavizadeh et al. 2006). In another study, Sunil et al. (2014) determined that the total variation reached 99.76% in the first four axes in an onion germplasm collection collected from different parts of the Indian Peninsular region. Hancı and Gökçe (2016) found the morphological variability ratios to be 71.84% among accessions in nine main axes with eigen values >1 in Turkish onion genotypes. Our results were similar to those discussed in the literature. In addition, these results showed that the red and white onion populations are heterogeneous.

Grouping of red and white onion genotypes by cluster analysis

Cluster analysis is more sensitive and reliable when 25% of the total variation or more is explained by the first two or three axes in PCA (Mohammadi and Prasanna 2003; Kanal and Balkaya 2021). The data to be used in cluster analysis are evaluated taking the PCA results into consideration. Genetic similarity among genotypes was estimated using UPGMA cluster analysis based on morphological traits. The dendrogram of red onions obtained from cluster analysis is shown in Figure 1. In the dendrogram, dissimilarity coefficients among genotypes ranged from -0.14 to 0.31. At the result of cluster analysis based on 31 morphological traits, the red onions were divided into three clusters (Table 6).

Group A: The largest number of genotypes were clustered in this group (Table 6, Figure 1). When compared with the genotypes in other groups, traits like intensity of foliage's green colour L (39.9), bulb weight (106.9 g), root disc diameter (13.2 mm) and the intensity of dry skin colour b (13.2) were found to be higher than in groups B and C (Table 7). A wide bulb neck width is an undesirable trait in onion varieties. The red onion genotypes in this group had the highest bulb neck width (15.2 mm). The bulb shape of genotypes in Group A were round, broadly egg-like, oval and broadly oval. Compared to other groups, foliage waxiness was not detected in this group (Table 7).

Group B: The lowest number of genotypes (two genotypes) was clustered in this group (Table 6). The average bulb height (50.6 mm) of the genotypes in this group was higher than in the other groups (Table 7). All the genotypes had dark green foliage, and were egg and oval-shaped. The pseudo stem diameter (7.9 mm) and bulb neck width (10.8 mm) of the genotypes in group B were thinner than in the other groups. The genotypes had hard bulbs. The bulb dry matter content (8.8%) was the lowest among the groups (Table 7).

Group C: Five genotypes were clustered in this group (Table 6). Traits such as the number of leaves (9.6), the intensity of green colour b (7.2), leaf length (55.4 cm), leaf diameter (12.1 mm), pseudo stem length (12.0 cm), pseudo stem diameter (9.6 mm), bulb diameter (64.1 mm), bulb dry matter content (12.0%) and the intensity of dry skin colour L (55.6) were higher than in the other groups (Table 7). The red onion genotypes in Group C were oval or broadly oval-shaped. In terms of dry skin thickness, the genotypes in this group had thin skin. All the genotypes were found to have a sweet taste according to the degustation panel test. The bulb height (44.2 mm) was lower than in group A and group B (Table 7).

The dendrogram of the white onion genotypes is shown in Figure 2. Genotypes were clustered in two groups and four subgroups (Table 8). In the dendrogram, the dissimilarity coefficients among genotypes ranged from -0.14 to 0.31. The general characteristics of these groups are given below.

Group A: Five genotypes are clustered in this group (Table 8, Figure 2). The genotypes in this group were superior to Group B in terms of traits such as the average number of leaves (9.2), the intensity of green colour b (5.0), leaf length (55.4 cm), leaf diameter (11.4 mm), pseudo stem diameter (9.2 mm), and

bulb dry matter content (9.8%) (Table 9). The bulbs of the genotypes in this group were the hardest. The bulbs were round and broadly oval. The genotypes in Group A were harvested earliest.

Group B: This group consisted of four genotypes (Table 8, Figure 2). The genotypes in this group were superior to group A in terms of the intensity of green colour L (39.8), pseudo stem length (11.0 cm), bulb weight (128.0 g), bulb height (57.2 mm), bulb diameter (66.3 mm), root disc diameter (13.1 mm), the intensity of dry skin colour L (69.4) and the intensity of dry skin colour b (9.4) (Table 9). The bulbs were round, rhombic and oval. Foliage waxiness was present in all genotypes.

Onion populations have been grouped by cluster analysis by many researchers. Mousavizadeh et al. (2006) determined that a population formed from 20 local landraces and two hybrid varieties clustered in four main groups. Mallor et al. (2011) found three main groups in terms of morphological and physico-chemical characteristics for 86 local onion genetic resources. Similarly, Manbachi et al. (2012) classified 23 onion genotypes into three groups by cluster analysis. In another study, Manjunathagowda et al. (2021) studied the genetic diversity and variability among inbred onion lines at the S_1 level. In the cluster analysis, a high level of difference was found in group II and group IV. The results of the present study were similar to the literature mentioned above in terms of the number of groups formed in the population.

Evaluation of the principal component analysis and cluster analysis results for red and white onion genotypes

As a result of the research, it can be said that the factor coefficients of the groups that emerged in the cluster analysis and PCA for all onion genotypes were located in similar coordinates in the 3D PCA graph (Figure 3, Figure 4). It seems clear which axes' characteristics caused the distribution of onion genotypes according to the groups. The present study determined that there was a high level of variation among genotypes in terms of characteristics for the green (fresh) and dry bulb harvest periods. Genotypes were clustered in the same groups in terms of characteristics in both harvest periods. These results will assist in the elimination of closely related genotypes. In addition, it will also be possible to determine the most distant relative genotypes in terms of morphological characteristics, and a high rate of heterosis will be obtained by crossing these genotypes. There was no correlation between the origins of the onion genotypes and the similarities revealed as a result of multivariate analysis. This shows that they were introduced to their place of origin much earlier. Onion genotypes show differences as a result of natural selection in different ecologies in the same country.

Phenotypical diversity and genetic variability are very important for the achievement of breeding programs (Balkaya and Ergün 2007). The principal aim in breeding programs is to select plants with desired characteristics and a wide genetic variation. Detection of the genetic diversity of existing germplasm collections and revealing its distribution will provide significant benefits for breeding strategies. It will thus be possible to make more precise decisions using molecular breeding methods for the white and red onion genotypes studied.

This study determined phenotypic diversity using multivariate analysis in red and white onion genotypes collected from different countries. The sources of morphological variation were determined in both onion types. The research results may assist onion breeders in establishing a heterogeneous gene pool. In a further study, we plan to select superior onion genotypes through cooperation between the university and the private sector. The aim is thus to develop high-quality, new hybrid varieties in the near future.

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Table 1. Genotype code, accession number and geographical origins of 23 *Allium cepa* genotypes studied.

Genotype Code	Accession Number	Origin	Genotype Code	Accession Number	Origin
RO1	PI 546208	USA	WO1	PI 546189	USA
RO2	PI 546118	USA	WO2	PI 546106	USA
RO3	PI 344253	Türkiye	WO3	PI 546115	USA
RO4	PI 344256	Türkiye	WO4	PI 546182	USA
RO5	PI 344261	Türkiye	WO5	PI 264326	Spain
RO6	PI 264316	Spain	WO6	PI 546093	USA
RO7	PI 264325	Spain	WO7	PI 249902	Spain
RO8	PI 171475	Türkiye	WO8	PI 280554	Russia
RO9	PI 174024	Türkiye	WO9	PI 289690	Australia
RO10	PI 179627	India			
RO11	PI 220081	Afghanistan			
RO12	PI 232068	South Africa			
RO13	PI 546096	USA			
RO14	PI 357217	North Macedonia			

Table 2. List of morphological characters used in the characterization of *Allium cepa* populations.

Plant number of leaves per pseudo stem	(1) Few (2) Medium (3) Many
Foliage colour	(1) Light green (2) Green (3) Dark green
Foliage intensity of green colour L	
Foliage intensity of green colour a	This was measured with a digital colour measuring device (chromameter).
Foliage intensity of green colour b	
Leaf length, cm	Leaf lengths were measured with a ruler.
Leaf diameter, mm	Leaf widths were measured with a digital caliper.
Pseudo stem length, cm	Body lengths were measured with a ruler.
Pseudo stem diameter, mm	Body diameters were measured with a digital caliper.
Foliage attitude	(1) Erect (2) Semi-erect (3) Horizontal
Foliage waxiness	(1) Strong (2) Absent or weak
Waxiness degree	(1) Few (2) Medium (3) Many
Foliage cranking	(1) Absent or weak (2) Intermediate (3) Strong

Table 3. List of morphological characters used in the characterization of *Allium cepa* populations.

Bulb weight, g	Three onions from each genotype were weighed with a 0.1 g precision digital scale.
Bulb height, mm	The lengths of the onions were measured with a digital caliper.
Bulb diameter, mm	The diameter of the onions was measured with a digital caliper.
Bulb width of neck, mm	The neck width of the onions was measured with a digital caliper.
Root disc diameter, mm	The root disc diameter values of onions were measured with digital caliper.
Bulb dry matter content, %	This was determined as a result of the measurement of onion juice in a digital refractometer.
Intensity of dry skin colour L	
Intensity of dry skin colour a	This was measured with a digital colour measuring device (Chromameter).
Intensity of dry skin colour b	
Bulb hardness	(1) Soft (2) Medium (3) Hard
Bulb position of maximum diameter	(1) Towards stem end (2) at middle (3) Towards root end
Bulb shape of stem end	(1) Depressed (2) Flat (3) Slightly raised (4) Rounded (5) Slightly sloping (6) Strongly sloping
Bulb shape of root end	(1) Depressed (2) Flat (3) Rounded (4) Strongly tapered
Bulb shape	(1) Elliptic (2) Medium ovate (3) Broad elliptic (4) Circular (5) Broad ovate (6) Broad obovate (7) Rhombic (8) Transverse medium elliptic (9) Transverse narrow elliptic
Degustation analysis	(1) Pain (2) Sweet
Time of harvest	(1) Early (2) Medium (3) Late
Thickness of dry skin	(1) Thin (2) Medium (3) Thick
Bulb base colour of dry skin	(1) Red (2) White

Table 4. Principal component analysis of characters associated with red onion populations.

	PC Axis							
Eigenvalues	6.8	6.3	4.1	3.0	2.4	2.3	1.7	1.3
Variation, %	22.1	20.5	13.1	9.7	7.8	7.3	5.6	4.1
Cumulative variation, %	22.1	42.5	55.7	65.3	73.1	80.5	86.1	90.2
	Eigen Vectors							
Traits	**PC 1**	**PC 2**	**PC 3**	**PC 4**	**PC 5**	**PC 6**	**PC 7**	**PC 8**
Plant number of leaves per pseudo stem	-0.07	0.05	**-0.93**	-0.03	-0.02	0.10	0.04	-0.22
Foliage colour	0.20	0.02	**0.30**	0.03	-0.79	-0.07	-0.40	0.03
Foliage intensity of green colour L	0.06	0.01	**-0.41**	-0.001	0.12	0.16	-0.11	0.09
Foliage intensity of green colour a	0.01	-0.19	0.13	-0.09	-0.25	-0.05	**-0.91**	-0.15
Foliage intensity of green colour b	0.001	0.14	0.07	0.08	0.20	0.02	**0.92**	0.21
Leaf length, cm	**-0.43**	0.46	-0.26	-0.11	0.20	-0.19	0.27	0.09
Leaf diameter, mm	-0.17	0.17	**-0.50**	-0.07	0.15	-0.55	0.48	-0.02
Pseudo stem length, cm	-0.07	0.23	**-0.47**	0.18	-0.06	0.007	0.18	0.17
Pseudo stem diameter, mm	-0.07	0.05	**-0.93**	-0.03	-0.02	0.10	0.04	-0.22
Foliage attitude	-0.10	0.26	0.23	0.15	**0.62**	-0.43	0.03	0.03
Foliage waxiness	0.18	0.08	0.01	0.01	**0.93**	-0.22	0.03	0.07
Waxiness degree	-0.05	-0.01	-0.08	0.07	**-0.88**	0.10	-0.28	-0.20
Foliage cranking	-0.17	0.11	-0.21	0.27	-0.17	-0.06	0.05	-0.18
Bulb weight, g	-0.06	-0.005	0.25	0.05	0.22	-0.14	0.20	**0.88**
Bulb height, mm	**0.32**	-0.03	0.26	0.10	0.17	-0.78	-0.009	0.33
Bulb diameter, mm	-0.09	0.15	0.10	0.05	-0.006	0.21	0.17	**0.93**
Bulb width of neck, mm	-0.006	0.09	-0.07	**-0.89**	0.01	-0.14	-0.32	0.17
Root disc diameter, mm	**0.31**	0.56	0.16	-0.34	0.04	-0.11	0.06	0.61
Bulb dry matter content, %	-0.26	**0.42**	-0.27	-0.34	-0.18	0.25	-0.06	-0.50
Intensity of dry skin colour L	**-0.91**	-0.03	-0.04	-0.08	-0.03	0.22	0.11	0.02
Intensity of dry skin colour a	-0.16	-0.003	**0.47**	0.58	-0.35	-0.03	-0.20	0.28
Intensity of dry skin colour b	**-0.87**	0.14	-0.36	-0.12	0.009	0.07	-0.14	-0.04
Bulb hardness	0.19	-0.09	-0.09	**0.86**	0.05	-0.24	-0.10	0.20
Bulb position of maximum diameter	**0.67**	-0.07	-0.07	0.14	-0.25	0.13	-0.40	-0.09
Bulb shape of stem end	**0.48**	0.06	0.20	0.34	0.06	-0.35	-0.46	-0.26
Bulb shape of root end	0.15	**0.38**	-0.01	0.06	0.28	-0.59	0.30	-0.11
Bulb shape	-0.22	0.04	-0.15	-0.01	-0.12	**0.88**	0.20	0.16
Degustation analysis	-0.11	-0.07	-0.06	0.13	**-0.34**	0.31	0.08	0.11
Time of harvest	**0.75**	0.009	-0.11	-0.33	0.37	-0.34	0.07	0.02
Thickness of dry skin	0.17	**-0.85**	0.08	0.10	-0.12	-0.01	-0.39	-0.18
Bulb base colour of dry skin	**-0.34**	-0.44	-0.67	0.06	0.05	0.13	-0.07	0.06

Table 5. Principal component analysis of characters associated with white onion populations.

	PC Axis						
Eigenvalues	7.4	6.3	3.9	3.9	2.8	2.3	1.4
Variation, %	25.4	21.6	13.5	13.3	9.8	8.0	4.8
Cumulative variation, %	25.4	47.1	60.6	73.9	83.7	91.6	96.4
	Eigen Vectors						
Trait	**PC 1**	**PC 2**	**PC 3**	**PC 4**	**PC 5**	**PC 6**	**PC 7**
Plant number of leaves per pseudo stem	-0.15	0.09	0.01	**-0.98**	0.07	0.03	-0.05
Foliage colour	-0.14	**-0.78**	0.30	0.30	-0.19	0.27	0.24
Foliage intensity of green colour L	-0.05	-0.08	0.23	**0.49**	0.83	-0.04	0.04
Foliage intensity of green colour a	0.01	-0.21	**-0.33**	-0.87	-0.07	-0.09	0.02
Foliage intensity of green colour b	0.19	0.29	**0.51**	0.60	0.07	0.36	-0.17
Leaf length, cm	**0.69**	-0.12	0.40	0.13	-0.33	-0.40	0.22
Leaf diameter, mm	0.23	**0.33**	0.42	-0.41	-0.33	-0.55	0.09
Pseudo stem length, cm	**0.30**	-0.21	-0.36	0.25	-0.73	-0.01	0.25
Pseudo stem diameter, mm	-0.15	0.09	0.01	**-0.98**	0.07	0.03	-0.05
Foliage attitude	0.02	-0.07	0.16	0.01	0.08	-0.03	**0.98**
Foliage waxiness	**0.36**	0.40	0.26	-0.32	0.10	0.61	-0.27
Waxiness degree	-0.07	**-0.82**	-0.40	0.14	-0.15	-0.04	-0.07
Foliage cranking	**0.40**	-0.27	0.08	0.27	0.08	-0.79	-0.09
Bulb weight, g	**-0.95**	-0.13	0.11	-0.03	0.04	0.10	0.07
Bulb height, mm	**-0.52**	-0.35	0.58	0.15	-0.32	0.23	0.26
Bulb diameter, mm	**-0.86**	-0.08	-0.33	-0.25	0.08	-0.06	-0.09
Bulb width of neck, mm	0.18	0.04	**0.83**	0.03	0.18	-0.13	0.03
Root disc diameter, mm	0.23	0.01	**0.49**	0.61	-0.34	-0.23	0.26
Bulb dry matter content, %	0.28	**-0.59**	0.06	-0.56	0.36	0.33	0.09
Intensity of dry skin colour L	-0.01	**0.97**	-0.01	0.16	0.10	0.08	0.02
Intensity of dry skin colour a	-0.28	**-0.83**	-0.45	-0.07	0.09	0.10	-0.02
Intensity of dry skin colour b	0.12	**0.79**	-0.37	0.36	-0.18	0.09	0.05
Bulb hardness	**-0.62**	0.35	0.06	-0.48	-0.15	-0.05	-0.46
Bulb position of maximum diameter	0.08	0.14	-0.19	-0.26	**0.90**	-0.04	0.22
Bulb shape of stem end	0.23	**-0.54**	0.57	0.01	-0.40	0.01	0.40
Bulb shape of root end	**0.33**	-0.14	0.83	0.29	0.14	-0.19	0.18
Bulb shape	**0.36**	-0.19	-0.88	-0.10	0.04	-0.20	-0.01
Degustation analysis	0.02	**0.37**	0.03	-0.23	0.12	-0.88	-0.01
Time of harvest	0.28	**-0.87**	0.01	0.18	-0.10	-0.01	0.29
Thickness of dry skin	-	-	-	-	-	-	-
Bulb base colour of dry skin	-	-	-	-	-	-	-

Table 6. Red onion genotype group and subgroups obtained by principal component analysis.

Groups	Subgroups	Genotypes	Total Genotype Number
A	1	RO1, RO3, RO5	7
	2	RO7, RO9, RO11, RO13	
B	1	RO2, RO12	2
C	1	RO4, RO6, RO8	5
	2	RO10, RO14	
Total	**5**		**14**

Table 7. Average values of the characteristics of red onion genotypes in PC groups.

Trait	A	B	C
Plant number of leaves per pseudo stem	9.2±2.2	7.9±2.7	9.6±1.7
Foliage colour	1, 2, 3	3	2, 3
Foliage intensity of green colour L	39.9±2.0	38.7±1.4	39.2±3.0
Foliage intensity of green colour a	-6.9±1.7	-6.2±1.5	-10.1±1.4
Foliage intensity of green colour b	3.1±2.1	2.6±1.3	7.2±2.5
Leaf length, cm	54.7±3.2	42.9±2.4	55.4±2.5
Leaf diameter, mm	11.8±1.5	9.9±3.6	12.1±0.8
Pseudo stem length, cm	10.6±2.1	8.3±1.3	12.0±0.6
Pseudo stem diameter, mm	9.2±2.2	7.9±2.7	9.6±1.7
Foliage attitude	1, 2	1	1
Foliage waxiness	1, 2	1	1
Waxiness degree	1, 3	3	2, 3
Foliage cranking	1, 2, 3	1	1, 2, 3
Bulb weight, g	106.9±16.8	78.7±5.7	99.6±41.0
Bulb height, mm	49.8±7.9	50.6±10.3	44.2±8.2
Bulb diameter, mm	63.9±4.0	54.2±4.9	64.1±11.7
Bulb width of neck, mm	15.2±3.5	10.8±1.6	12.1±1.7
Root disc diameter, mm	13.2±1.4	10.6±0.4	13.1±1.2
Bulb dry matter content, %	10.8±1.7	8.8±1.2	12.0±3.1
Intensity of dry skin colour L	54.9±18.1	37.7±11.4	55.6±24.3
Intensity of dry skin colour a	15.5±7.0	19.2±6.2	15.1±4.5
Intensity of dry skin colour b	13.2±8.5	1.5±1.1	8.2±9.0
Bulb hardness	2, 3	3	2, 3
Bulb position of maximum diameter	2, 3	3	2, 3
Bulb shape of stem end	2, 3, 4	4, 5	2, 3, 4
Bulb shape of root end	2, 3, 4	1, 3	2, 3, 4
Bulb shape	4, 5, 8, 9	2, 8	8, 9
Degustation analysis	1, 2	1, 2	2
Time of harvest	1, 3	1, 2	1, 2
Thickness of dry skin	1, 2	2, 3	1
Bulb base colour of dry skin	1, 2	1	1

Table 8. White onion genotype group and subgroups obtained by principal component analysis.

Groups	Subgroups	Genotypes	Total Genotype Number
A	1	WO1, WO3, WO5	5
	2	WO7, WO9	
B	1	WO2, WO4, WO8w	4
	2	WO6	
Total	**4**		**9**

Table 9. Average values of the characteristics of white onion genotypes in PC groups.

Trait	A	B
Plant number of leaves per pseudo stem	9.2±0.4	9.1±0.6
Foliage colour	2, 3	2, 3
Foliage intensity of green colour L	39.3±3.9	39.8±2.1
Foliage intensity of green colour a	-7.8±1.5	-7.8±1.7
Foliage intensity of green colour b	5.0±2.8	3.9±2.3
Leaf length, cm	55.4±6.3	53.9±9.5
Leaf diameter, mm	11.4±1.6	10.5±2.1
Pseudo stem length, cm	10.2±2.3	11.0±1.4
Pseudo stem diameter, mm	9.2±0.4	9.1±0.6
Foliage attitude	1	1, 2
Foliage waxiness	1, 2	1
Waxiness degree	1, 2, 3	1, 3
Foliage cranking	1, 2, 3	1, 2, 3
Bulb weight, g	123.6±47.1	128.0±44.5
Bulb height, mm	56.5±13.3	57.2±11.5
Bulb diameter, mm	66.2±8.3	66.3±9.1
Bulb width of neck, mm	12.3±5.5	10.7±4.8
Root disc diameter, mm	12.7±2.1	13.1±1.4
Bulb dry matter content, %	9.8±1.8	9.7±2.3
Intensity of dry skin colour L	63.6±15.7	69.4±17.8
Intensity of dry skin colour a	-0.73±2.1	-0.4±1.7
Intensity of dry skin colour b	6.0±4.4	9.4±6.5
Bulb hardness	3	1, 3
Bulb position of maximum diameter	1, 2	2
Bulb shape of stem end	3, 4	2, 3, 4
Bulb shape of root end	2, 3, 4	1, 3, 4
Bulb shape	4, 9	4, 7, 8
Degustation analysis	1, 2	1, 2
Time of harvest	1, 2	1, 2, 3

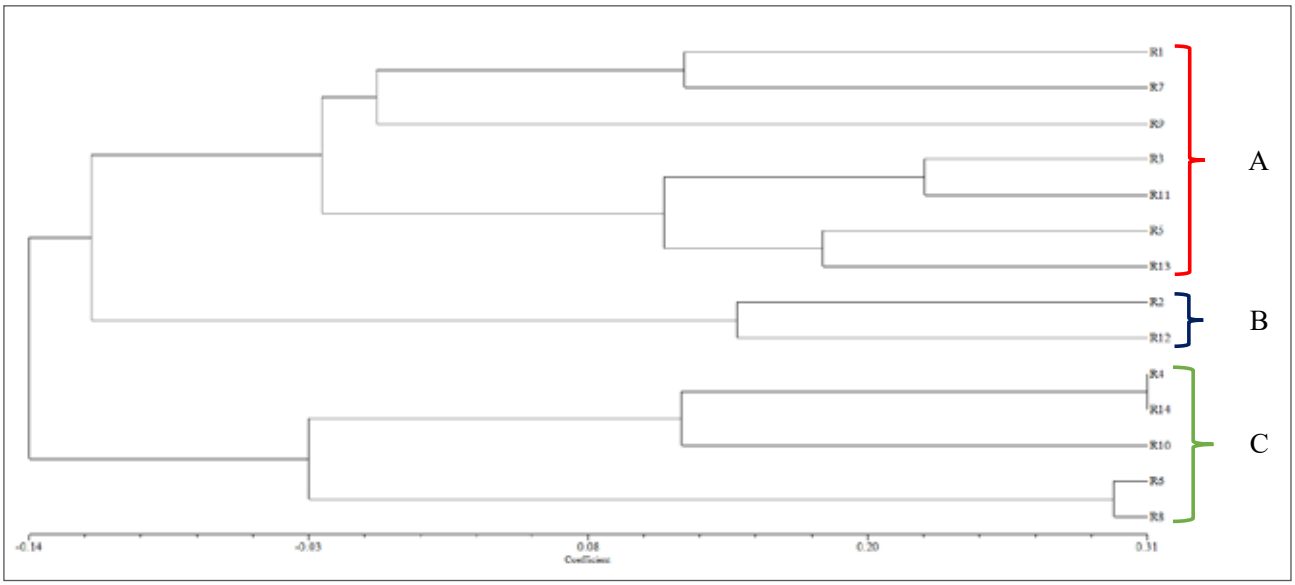

Figure 1. Phenotypical groupings of red onion genotypes according to cluster analysis.

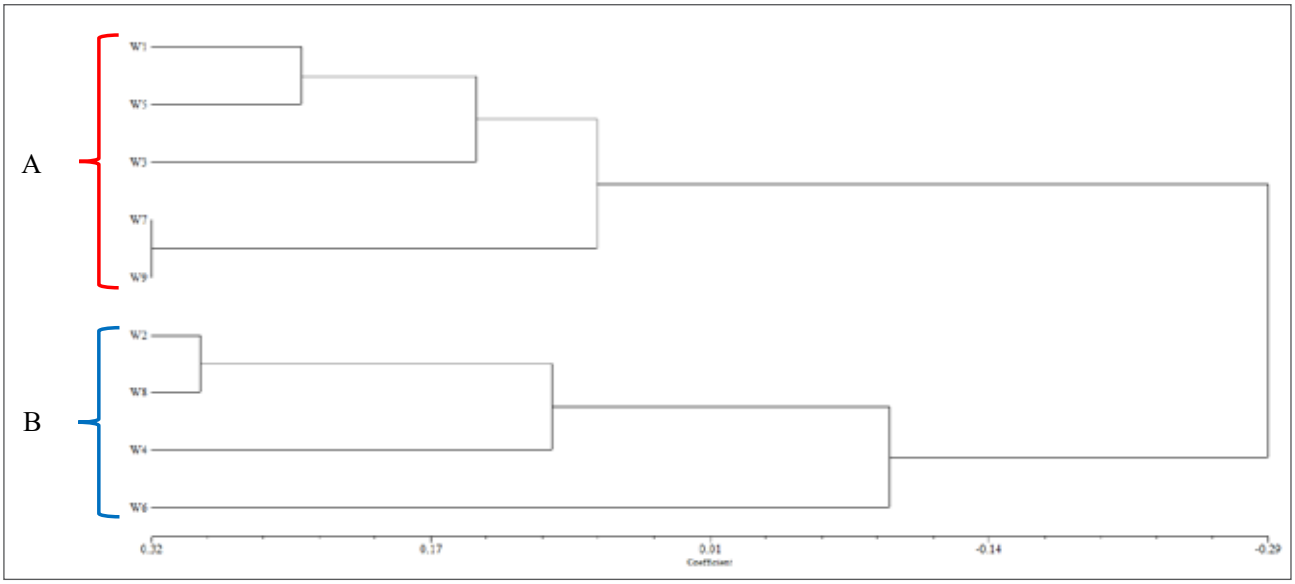

Figure 2. Phenotypical groupings of white onion genotypes according to cluster analysis.

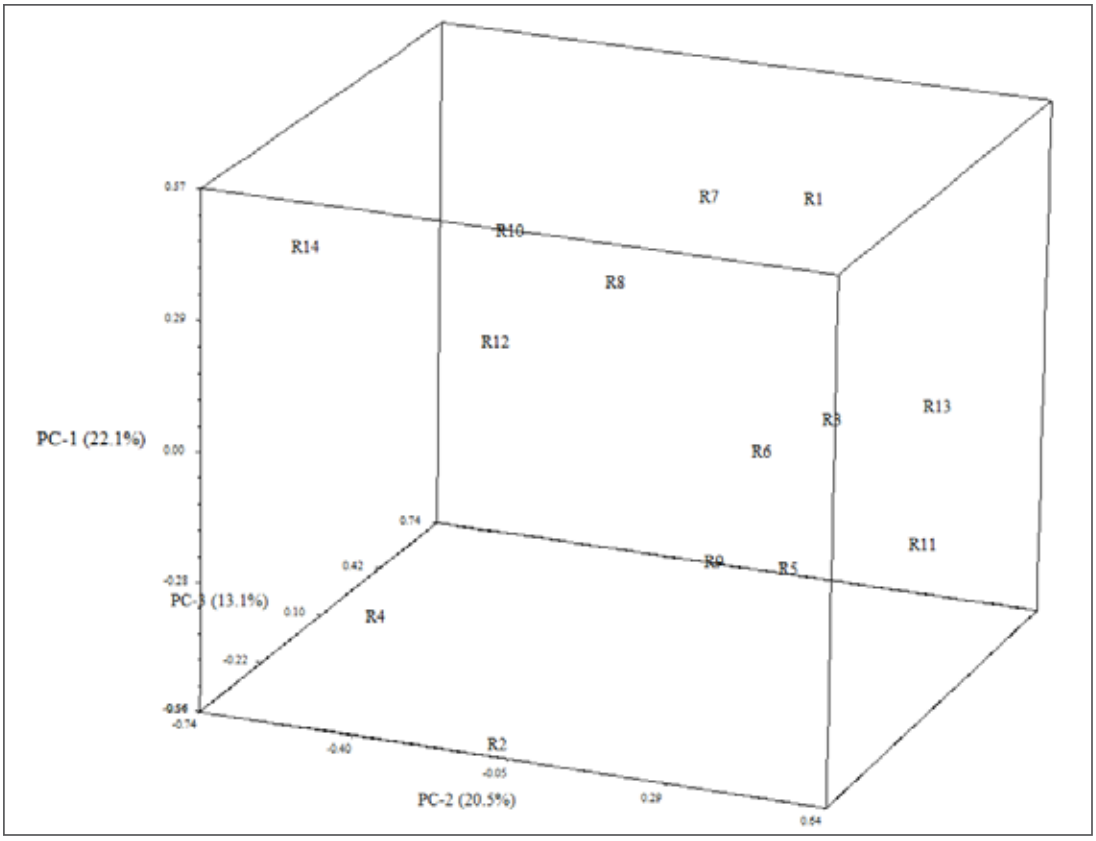

Figure 3. Three-dimensional diagram of the similarity of red onion genotypes with each other according to the first three PC values obtained by principal component analysis.

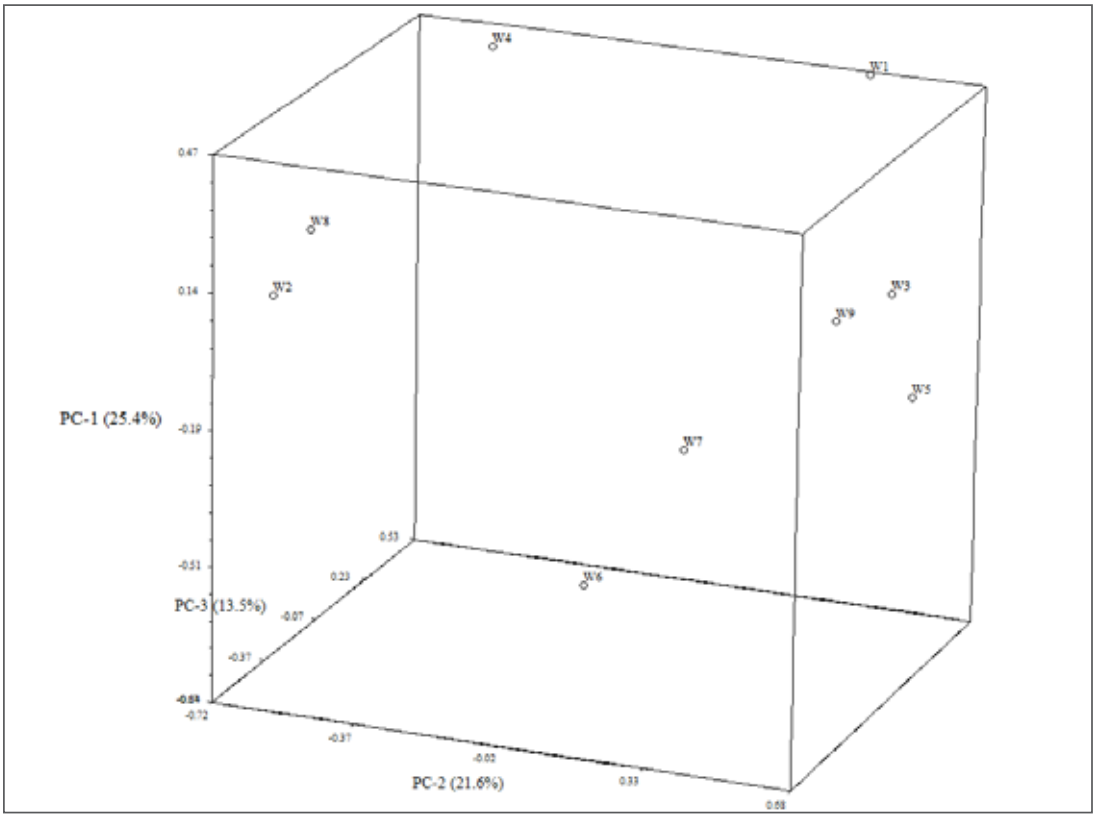

Figure 4. Three-dimensional diagram of the similarity of white onion genotypes with each other according to the first three PC values obtained by principal component analysis.

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