

Evaluation of morphological variability in Tombul (*Corylus avellana* L.) hazelnut population

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Abstract

In the Black Sea Region of Türkiye, hazelnuts are traditionally grown in a multi-stemmed bush ('ocak' in Turkish) system. The study was conducted to assess the morphological variability in the 'Tombul' (*Corylus avellana* L.) hazelnut population of Piraziz district of Giresun province (Eastern Black Sea region, Türkiye), where hazelnut cultivation backs to ancient times. Morphological variability was evaluated based on regular plant yield, superior nut quality and late leafing characteristics in 100 Tombul clones in the Tombul hazelnut population of the district. In the clones, nut yield per plant varied from 179.0-547.4 g. Nut weight, kernel weight and kernel ratio ranged from 1.22-2.01 g, 0.58-1.11 g, 46.37-55.84%, respectively. Shell thickness was determined between 0.67-1.43 mm. Good kernel was from 57-99%. According to PCA analysis results, the first two components accounted for 58.7% of total variability and were associated with several yield and nut traits. Nut weight showed a strong positive correlation ($r=0.97^{***}$) with kernel weight. As a result, a wide variation was determined among the clones for the investigated traits. Five clones (T-1, T-10, T-12, T-14 and T-15) have been identified as promising candidates for preliminary selection due to their morphological traits. Future studies should focus on their biochemical and molecular characterization.

Keywords: Hazelnut, Tombul, clone, nut traits, nut yield, variation.

Zusammenfassung

Bewertung der morphologischen Variabilität in der Tombul-Haselnusspopulation (*Corylus avellana* L.). In der türkischen Schwarzmeerregion werden Haselnüsse traditionell als mehrstämmige Strauchform ('ocak' auf Türkisch) angebaut. Ziel der Studie war die Untersuchung der morphologischen Variabilität der Haselsorte 'Tombul' (*Corylus avellana* L.) im Bezirk Piraziz der Provinz Giresun (östliche Schwarzmeerregion, Türkei), wo der Haselnussanbau bis in die Antike zurückreicht. Die morphologische Variabilität wurde anhand des regelmäßigen Pflanzenertrags, der hohen Nussqualität und des späten Blattaustriebs von 100 Tombul-Klonen innerhalb der Population des Bezirks bewertet. Der Nussertrag pro Pflanze variierte zwischen 179.0-547.4 g. Nussgewicht, Kerngewicht und Kernanteil lagen zwischen

1.22-2.01 g, 0.58-1.11 g bzw. 46.37-55.84 %. Die Schalendicke lag zwischen 0.67 mm und 1.43 mm. Der Anteil guter Kerne betrug 57-99 %. Laut PCA-Analyse erklärten die ersten beiden Komponenten 58.7 % der Gesamtvariabilität und korrelierten mit verschiedenen Ertrags- und Nussmerkmalen. Das Nussgewicht zeigte eine starke positive Korrelation ($r = 0.97^{***}$) mit dem Kerngewicht. Daraus ergab sich eine große Variation der untersuchten Merkmale zwischen den Klonen. Fünf Klone (T-1, T-10, T-12, T-14 und T-15) wurden aufgrund ihrer morphologischen Merkmale als vielversprechende Kandidaten für eine Vorauswahl identifiziert. Zukünftige Studien sollten sich auf deren biochemische und molekulare Charakterisierung konzentrieren.

Schlagwörter: Haselnuss, Tombul, Klon, Nussmerkmale, Nussertrag, Variation.

Introduction

Hazelnut (*Corylus avellana* L.) is one of the most popular nuts consumed worldwide because it is a valuable nutrient source for human nutrition and health (Alasalvar et al., 2009; Wani et al. 2020). Türkiye is the leading country in world hazelnut production and export, providing approximately 59,2% of world production with an annual production of 717,000 tons of in-shell hazelnuts. Italy (120,520 tons), USA (87,820 tons), Azerbaijan (75,697 tons) and Chile (73,237 tons) are other important hazelnut producing countries (FAOSTAT, 2026).

Hazelnuts grow in regions with climatic conditions characterized by cool summers and mild winters. Major production regions include the Black Sea Region of Türkiye, the Willamette Valley in Oregon (USA), Latium, Campania, Piedmont, around Lake Viterbo, Sicily in Italy, and Tarragona in Spain (Ercisli et al., 2011; Molnar, 2011). Additionally, hazelnut cultivation has recently expanded to new areas in the southern hemisphere, including Chile, Australia, and South Africa (Silvestri et al., 2021).

Around 20 regions in the world are dedicated to conserving hazelnut cultivars and genetic resources (Botta et al., 2019; Mehlenbacher and Molnar, 2021). These collections of genetic resource play a crucial role in preserving hazelnut germplasms for long-term use and providing access to plant breeders and producers. Currently, approximately 500 hazelnut cultivars have been identified, but only 20 are widely used in

cultivation (Botta et al., 2019). In Türkiye, which is rich in hazelnut genetic resources and the world's leading hazelnut producer, the most commonly grown cultivars are 'Tombul', 'Palaz', 'Çakıldak', 'Mincane', 'Foşa' and 'Kara' (Karakaya et al., 2023). Among these, 'Tombul' stands out for its rich nutrient content and superior nut quality. This cultivar is known for its round shape, high oil and protein content, excellent blanching properties, and its high suitability for consumption as dried nuts and industrial use (Alasalvar et al., 2009).

Over the centuries, Turkish hazelnut producers have been selectively choosing the best individuals and reproducing them through suckers (Thompson et al., 1996; Erdogan and Mehlenbacher, 2000). Interestingly, researchers have observed that even within a single variety, there can be differences in characteristics among the clones (Balta et al., 1997; Bostan and Islam, 1999). This led to the implementation of clonal selection programs to identify individuals excelling in the desirable traits such as vigor, nut traits, yield, and resistance to diseases and pests. This method is regarded as an effective method for identifying and selecting hazelnut genetic resources within existing populations (Petriccione et al., 2010; Turan, 2022; Kan and Islam, 2023; Ünver, 2024).

Assessment of morphological traits, including yield, nut and plant characteristics, is a common method for identifying hazelnut genetic resources (Islam, 2000; Turan, 2007; Petriccione et al.,

Materials and Methods

The study was conducted in the villages of Piraziz district at an altitude of 50-718 m located in the Eastern Black Sea region (Giresun, Türkiye), where hazelnut cultivation dates back to ancient times (Fig. 1). The study area is rainy-cool in the summer and rainy-mild in the winters. The average temperature is 16.3 °C. The highest average temperature is 26.1 °C in August, the lowest is 8.5 °C in January. The annual rainfall average is 1040 mm. The highest precipitation occurred in October with 175.5 mm, the lowest is recorded in April with 45.4 mm (TSMS, 2024).



Fig. 1: The location of the study (Piraziz, Giresun province, Türkiye)

Plant Materials

The multi-stemmed bushes ('ocak' in Turkish) belonging to Tombul hazelnut (*Corylus avellana* L.) cultivar grown in Piraziz district constituted the material of the study (Tab. 1). Plant numbers in the 'ocaks' of clones ranged between 5 and 10. Observations were made considering the

suggestions of hazelnut orchard owners. As a result of these observations, 100 clones from 31 different accessions that could be valuable, especially in terms of regular yield, superior fruit quality and late leafing characteristics were marked in the population.

Tab. 1: Distribution of 100 Tombul clones based on accessions in Piraziz district (Giresun, Türkiye)

Accession	Number of clones	Altitude (m)
Akçay	5	148-678
Alidede	5	538-587
Armutçukuru	2	569-648
Aydere	2	91-116
Balçıklı	4	413-538
Bozat	5	340-567
Bülbüllü	3	243-297
Çağlandere	1	661
Çayırköy	5	345-633
Deregözü	2	711-718
Eren	2	88-91
Esentepe	4	478-523
Etlikkiran	3	318-378
Gökçeali	5	411-566
Güneyköy	5	523-610
Güzelköy	1	718
Hasanşeyh	2	381-403
Kaleyani	2	133-168
Kargı	2	122-143
Kılıçlı	4	387-570
Maden	3	50-101
Medrese	4	540-670
Narlık	3	311-381
Nefsipiraziz	4	276-368
Örnekköy	3	411-610
Şerefli	4	525-693
Şeyhli	5	387-421
Şihkiran	2	153-187
Tepeköy	4	655-743
Yenimahalle	2	103-108
Yunusemre	2	701-718

Nut yield and number of nuts per cluster

All clusters on the plant were harvested and separated from their husks. The nuts were dried in the sun until the moisture content dropped to 6%, and then the plant yield was determined by weighing them. All clusters on the plant were counted as 1, 2, 3, etc., and the average number of clusters was calculated (Çalışkan et al., 2019).

Nut traits

Nut weight, kernel weight, kernel ratio, shell thickness, nut dimension (length, width, thickness and size), kernel dimension (length, width, thickness and size), nut and kernel shape index, good kernel, wrinkled kernel, empty kernel and double kernel were investigated as nut traits. Nut and kernel weight (g) were measured via digital balance (Radwag, Poland) with a readability of 0.01 g. Kernel ratio (%) was calculated as the ratio of kernel weight and nut weight. Shell thickness, nut and kernel dimensions (mm) were measured using a digital caliber (Mitutoyo, Japan) with a resolution of 0.01 mm. Nut and kernel shape index was calculated according to the formula $(((\text{nut width} + \text{nut thickness})/2)/\text{nut length})$. One hundred nuts were used to determine good, wrinkled, empty and double kernel ratios (İslam, 2000; Petriccione et al., 2010; Valentini et al., 2014; Güler and Balta, 2020; Balta et al., 2021).

Statistical Analysis

Data were analyzed with the JMP 16.0 (trial) (Cary, North Carolina, USA) statistical packet program. Descriptive statistics were determined for the investigated traits [minimum (min.), maximum (max.), mean, standard deviation (SD), and coefficient variance (CV)]. The yield and nut traits of investigated clones were used to principal components, biplot, clustering, and heatmap analyzes. Correlation analyses were also performed between the traits investigated.

Results and Discussion

Coefficient of variation (CV)

The highest CV was determined with the trait double kernel (1.32). It is followed by empty kernel ratio (0.62), wrinkled kernel ratio (0.36) and nut yield (0.22). The lowest CV was determined in the number of nuts per cluster and kernel ratio (0.03) (Tab. 2). Karakaya (2021) reported a coefficient of variation (CV) ranging from 0.0 to 2.02 in 145 Palaz hazelnut clones and from 0.0 to 4.29 in 96 Çakıldak hazelnut clones. In a study conducted by Uzun (2021), the coefficient of variation (CV) was recorded to range from 0.0 to 2.01 in 155 Tombul hazelnut clones and from 0.0 to 2.24 in 53 Karafındık hazelnut clones. Consistent with the findings of the current investigation, both researchers reported a high coefficient of variation (CV) for the double kernel, empty kernel, wrinkled kernel, and nut yield traits.

Nut yield and number of nuts per cluster

High yield is a desired trait for hazelnut breeding programs. The selection of high-yielding individuals from the existing population enabled the development of productive varieties in hazelnut breeding programs (Botta et al., 2019). The variety, ecological factors, cultivation conditions, pollination (pollinator), and number of stems per shrub are effective factors in the hazelnut yield (Çalışkan et al., 2019; Balta et al., 2021).

The investigated clones exhibited a wide variation in terms of nut yield. Indeed, plant yield was one of the traits with the highest CV. In the clones, nut yield varied between 179.0 and 547.4 g (Tab. 2; Fig. 2). Turan (2007) reported that plant yield in Tombul hazelnut clones ranged from 140 to 2250 g in the Bulancak region. Similarly, Göğüs (2015) noted from 390 to 1364 g in the Tirebolu district. İslam and Çalış (2018) stated between 420 and 454 g in the Perşembe region. Uzun (2021) reported the range of 134 to 797 g in the Fatsa district. The nut yield of the clones was similar to

those of Islam and Çalış (2018) and Uzun (2021), but lower than those of other researchers. Furthermore, two clones (T-14 and T-12) with nut yields of 500 g or higher yielded significant results. Some observed differences in nut yield could be due to genetic structure, ecological factors (particularly drought and frost), and cultivation conditions.

Tab. 2: The range of nut and plant traits in 100 clones in the Tombul hazelnut population

Traits	Abbreviation	Unit	Min.	Max.	Mean	SD	CV
Nut yield	NY	g	179.0	547.4	340.1	75.0	0.22
Number of nuts in cluster	NNC	number	2.45	3.04	2.71	0.09	0.03
Nut weight	NW	g	1.22	2.01	1.58	0.15	0.10
Kernel weight	KW	g	0.58	1.11	0.81	0.10	0.12
Kernel ratio	KR	%	46.37	55.84	50.83	1.74	0.03
Shell thickness	ST	mm	0.67	1.43	1.04	0.10	0.10
Nut length	NL	mm	14.68	20.55	16.76	1.16	0.07
Nut width	NWt	mm	13.24	17.89	15.39	1.10	0.07
Nut thickness	NT	mm	11.97	16.76	14.28	1.08	0.08
Nut size	NS	mm	13.48	17.92	15.44	1.04	0.07
Kernel length	KL	mm	10.12	15.70	13.42	1.06	0.08
Kernel width	KWt	mm	9.45	14.11	12.47	1.13	0.09
Kernel thickness	KT	mm	7.41	14.17	11.38	1.30	0.11
Kernel size	KS	mm	9.25	14.58	12.39	1.14	0.09
Nut shape index	NSI	-	1.05	1.26	1.13	0.04	0.04
Kernel shape index	KSI	-	1.02	1.29	1.13	0.05	0.04
Good kernel ratio	GKR	%	57	99	72.5	11.5	0.16
Wrinkled kernel ratio	WKR	%	1	32	18.1	6.6	0.36
Empty kernel ratio	EKR	%	0	16	9.0	5.6	0.62
Double kernel ratio	DKR	%	0	2	0.5	0.6	1.32

SD: Standard deviation; CV: Coefficient of variation

The number of nuts per cluster has a high heritability (0.70) (Thompson et al., 1996) and is an important trait affecting plant yield. In the accessions investigated, the number of nuts per cluster ranged from 2.45 to 3.04. In previous studies, the number of nuts per cluster in Tombul hazelnut clones were reported as 3.49 in the Samsun country by Beyhan and Demir (2001), 2.08-4.36 in the Bulancak region by Turan (2007), 2.54-3.58 in the Perşembe district by Çalış (2010), 2.15-4.38 in the Giresun and Trabzon regions by Kalkışım and Balık (2012), and 2.4-3.9 in the Fatsa district by Uzun (2021). The number of nuts per cluster was reported as 2-3 in new foreign hazelnut cultivars such as ‘Monmouth’, ‘Hunterdon’, ‘Raritan’ (Molnar et al., 2020a, b, c), and 3 in ‘OSU 541.147’

(trademarked name-‘The Beast’) (Mehlenbacher et al., 2023). The genetic structure, ecological conditions, the number of female flowers pollinated, and technical and cultural practices (Beyhan and Marangoz, 2007; Liu et al., 2014; Balta et al., 2021) are influential factors for number of nuts per cluster. Furthermore, foreign pollination provides an increase in the number of nuts per cluster (Fattahi et al., 2014).

Nut traits

The heritability of nut weight, kernel weight and kernel percentage, which are important quality criteria in hazelnuts, are 0.63, 0.67 and 0.87, respectively (Yao and Mehlenbacher, 2000;

Mehlenbacher, 2018). High kernel percentage is a desirable trait in hazelnut breeding programs (Botta et al., 2019). In the clones investigated, nut weight ranged from 1.22 to 2.01 g, kernel weight varied from 0.58 to 1.11 g, and kernel ratio ranged from 46.37 to 55.84% (Tab. 2; Fig. 2). In the Tombul hazelnut clones, Balta et al. (1997) reported the range of 2.05 to 2.32 g for nut weight, 1.17 to 1.28 g for kernel weight, and 53.98 to 57.53% for kernel percentage in the Çarşamba region. Bostan (2001) determined nut weight between 1.43 and 1.95 g, kernel weight between 0.83 and 1.49 g, and kernel percentage between 52.86 and 58.90% in the Giresun district. Turan (2007) recorded a range of 1.59 to 2.49 g for nut weight, 0.75 to 1.24 g for kernel weight, and 45.70 to 54.30% for kernel percentage in the Bulancak region. The values of nut weight, kernel weight, and kernel percentage were reported 1.38 to 1.51 g, 0.77 to 0.85 g and 55.0 to 56.85% in Piraziz district (Akdemir, 2010), respectively. Göğüs (2015) determined nut weight between 1.54 and 2.33 g, kernel weight between 1.11 and 1.15 g, and kernel percentage between 50.71 and 55.15% in the Tirebolu district. In new foreign hazelnut cultivars such as 'Monmouth', 'Hunterdon', 'Raritan', and 'OSU 541.147', the nut weight, kernel weight and kernel percentage were reported as 2.46 to 2.51 g, 1.09 to 1.25 g, and 43.9 to 50.7%, respectively (Molnar et al., 2020a, b, c; Mehlenbacher et al., 2023). Nut weight, kernel weight and kernel percentage values of the clones were consistent with the researchers' findings. Also, three clones (T-1, T-10 and T-15) with nut weight over 2 g, kernel weight over 1 g and kernel percentage over 53% produced remarkable results. These clones have the potential to be used as genetic material in hazelnut breeding programs, pending future molecular and biochemical verification.

Shell thickness is a crucial factor that effects nut quality and correlated with kernel ratio. It is highly heritable (0.77) (Thompson, 1977). Also, thin shell is a desirable trait for hazelnut breeding programs. Shell thickness varied from 0.67 to 1.43 mm (Tab. 2; Fig. 2). In previous studies, shell thickness in Tombul hazelnut clones was reported to

range from 0.86 to 1.05 mm in the Ordu region by Islam (2000), 0.95 to 1.24 mm in the Bulancak district by Turan (2007), 0.87 to 1.13 mm in the Tirebolu region by Göğüs (2015), and 0.71 to 1.42 mm in Fatsa district by Uzun (2021). In the clones of foreign hazelnut cultivars (Tonda di Giffoni, Primval, Natval, Tonda Gentile delle Langhe), shell thickness was determined to range from 0.80 to 1.90 mm (Petriccione et al., 2009; Vicol et al., 2013; Valentini et al., 2014). The shell thickness values of the investigated clones were similar to the findings of the researchers. T-8 (0.68 mm) and T-3 (0.79 mm) clones yielded remarkable outcomes in terms of shell thickness. These clones can be used as genetic material to develop thin-shelled cultivars in hazelnut breeding programs, although their stable performance over multiple years remains to be validated.

Nut length varied from 14.68 to 20.55 mm, nut width ranged from 13.24 to 17.89 mm, nut thickness varied from 11.97 to 16.76 mm, and nut size ranged from 13.48 to 17.92 mm (Tab. 2). Different researchers reported that Tombul hazelnut clones had a range of 16.30 to 19.58 mm for nut length, 14.80 to 19.26 mm for nut width, 13.50 to 18.16 mm for nut thickness, and 15.10 to 18.82 mm for nut size (Balta et al., 1997; Islam, 2000; Turan, 2007; Göğüs, 2015; Uzun, 2021).

Kernel length varied from 10.12 to 15.70 mm, kernel width ranged from 9.45 to 14.11 mm, kernel thickness varied from 7.41 to 14.17 mm, and kernel size ranged from 9.25 to 14.58 mm (Tab. 2). In previous studies, different researchers recorded ranges of 12.44 to 15.0 mm for kernel length, 11.10 to 14.57 mm for kernel width, 10.50 to 14.38 mm for kernel thickness and 11.60 to 14.48 mm for kernel size in Tombul hazelnut clones grown in different districts of the Black Sea region (Beyhan and Demir, 2001; Turan, 2007; Göğüs, 2015; Uzun, 2021).

Nut and kernel size values of the clones were consistent with the researchers' findings. Also, most clones had a nut size of 16 mm or larger (33%), and a kernel size of 13 mm or above (41%). In this sense, many genotypes were grouped as extra (13-15 mm) according to the TSI kernel classification. These accessions can be used as genetic material for developing cultivars with large nuts.

The round shape is a crucial character for hazelnut breeding and industry (Botta et al., 2019). Nut shape index ranged from 1.05 to 1.26, kernel shape index varied from 1.02 to 1.29 mm (Tab. 2). Furthermore, all clones are round-shaped, indicating a high genetic potential for developing round-shaped hazelnut varieties in breeding programs.

In the Tombul hazelnut clones, Balta et al. (1997) reported the range of 1.05 to 1.12 for nut shape index in the Çarşamba district. Turan (2007) determined a nut shape index between 0.97 and 1.14 in the Bulancak region. Göğüs (2015) recorded a range of 1.02 to 1.13 for nut shape index and 1.02 to 1.13 for kernel shape index in the Tirebolu district. Uzun (2021) noted the range of 1.06 to 1.28 for nut shape index and 1.05 to 1.28 for kernel shape index in the Fatsa district. The investigated clones' nut and kernel shape index values were consistent with the researchers' reported reference values.

Good kernel and poor fill are crucial traits affecting yield with hazelnut, and a high good kernel ratio is a desirable character in hazelnut breeding (Botta et al., 2019). The good kernel ratio varied from 57 to 99% and wrinkled kernel ratio ranged from 1 to 32% (Tab. 2; Fig. 2). In previous studies, good kernel and wrinkled kernel ratios in Tombul hazelnut clones were reported from 75.91 to 91.0% and 0.0 to 11.3% in the Bulancak district by Turan (2007), 86.5 to 92.4% and 2.6 and 3.2% in the Ordu region by Serdar and Demir (2005), 16.67

to 90.0% and 0.0 to 82.67% in the Tirebolu region by Göğüs (2015), 87.70 to 91.57% and 6.12 to 8.76% in the Perşembe region by Islam and Çalış (2018), and 72.7 to 96.1% and 0.0 to 11.1% in the Fatsa district by Uzun (2021), respectively. Good kernel and wrinkled kernel ratios of the clones were consistent with the researchers' results.

Empty kernel formation is an undesirable event in fruit species whose seeds are edible, such as hazelnut. It is related to pollination and decreases with foreign pollination (Fattahi et al., 2014). Empty kernel ratio varied from 0 to 16% (Tab. 2). Different researchers have reported empty kernel ratio in Tombul hazelnut clones ranging from 2.0 to 22.67% in the Bulancak district (Turan 2007), 0.0 to 11.11% in the Tirebolu region (Göğüs 2015), 0.78 to 2.42% in the Perşembe region (Islam and Çalış 2018), and 0.0 to 15.3% in the Fatsa district (Uzun 2021). While the empty kernel ratio values of investigated clones were consistent with the findings of many researchers, they were lower than the findings of Islam and Çalış (2018). Some observed differences may be due to genetic structure, ecological factors, pollination and cultivation conditions.

Double kernels result from the development of two kernels in one nut and are an undesirable trait in hazelnut breeding. Also, double kernel is a trait with a high heritability (0.84) (Mehlenbacher, 2018). In the clones, double kernel ranged from 0 to 2% (Tab. 2). Many studies reported double kernel ratios ranging from 0.0 to 5.0% (Balta et al., 1997; Islam, 2000; Göğüs, 2015; Uzun, 2021). According to the classification of the United Nations (UN, 2010), nuts with more than 2% doubles are placed in the lower quality classes. In most of the clones investigated, the double kernel was 0%. In this respect, these clones could be used for improving this trait in hazelnut varieties with high double kernel ratios in breeding programs.

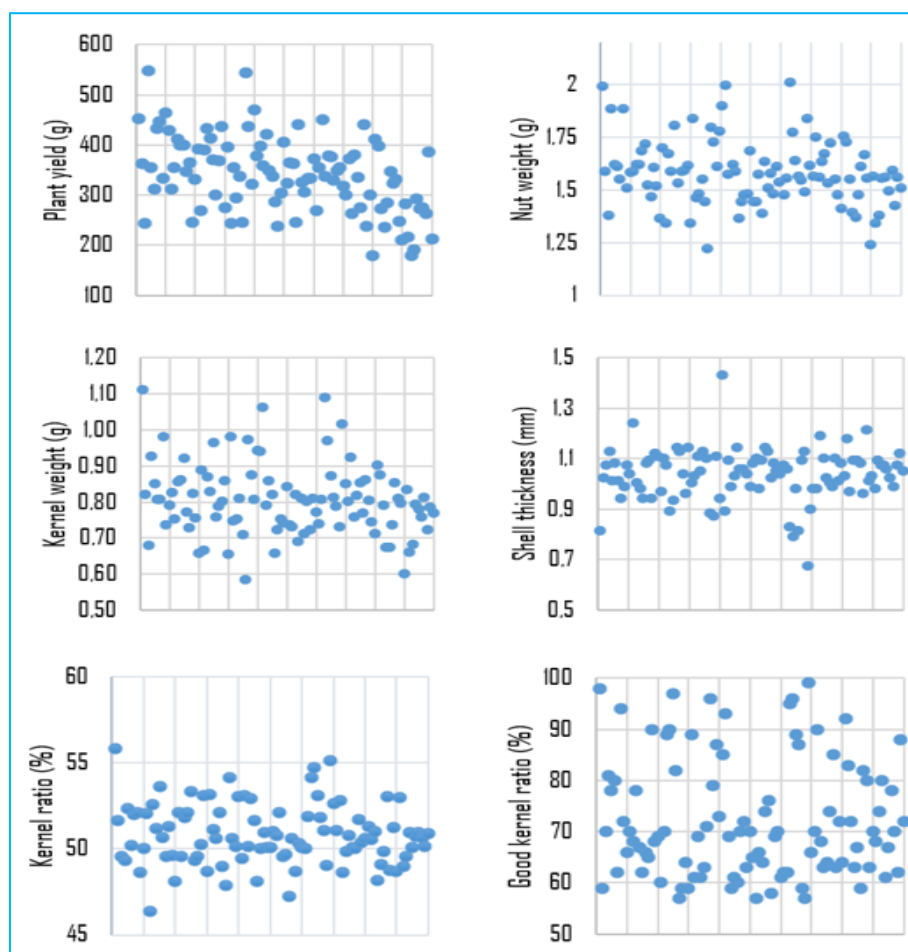


Fig. 2: Distribution of plant nut yield and some nut traits in 100 clones in the Tombul hazelnut population

Principle component (PCA), heatmap and correlation analysis

Twenty characters were used for PCA (principal component analysis). Six PCs had an eigenvalue greater than 1.0, explaining 87.0% of the total variation. The first three PCs accounted for 70.0% of the variability. PC 1 was mainly related to nut yield, nut weight, kernel weight, kernel ratio, shell thickness, nut length, nut width, nut thickness, nut size, good kernel, wrinkled kernel, empty kernel, and double kernel traits, explaining 37.7% of the total variability. PC 2, which explained 21.0% of the variability, was related to kernel length, kernel width, kernel thickness, kernel size, and kernel shape index. PC 3 was related to kernel ratio and explained 11.3% of total variability. PC 4, which explained 6.4% of the variability, was related to the number of nuts per cluster. PC 5 was related

to nut shape index by explaining 5.5% of the total variability. PC 6, which explained 5.1% of the variability, was related to kernel shape index (Tab. 3, Fig. 3). Similarly, Campa Negrillo (2021) reported positive correlation between nut weight, kernel weight, nut and kernel dimension (length, width and thickness) traits in the local hazelnut cultivars of Northern Spain and stated that the first two components explained 81.4% of the total variability. Karakaya et al. (2023) reported that the first three components accounted for 84.21% of the total variability in the hazelnut germplasm, and these components were associated with the traits kernel weight, nut weight, kernel percentage, nut width, nut thickness, nut length, nut size, nut shape index, kernel shape index, kernel width, kernel thickness, kernel length and kernel size. Several researchers reported similar results in Turkish hazelnut cultivars (Islam et al., 2005; Bak and Karadeniz, 2021).

Tab. 3: Principal component analysis of Tombul hazelnut clones

Traits	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6
Nut yield	0.52153*	-0.37262	0.34979	0.42384	0.25267	0.01387
Number of nuts in cluster	0.12370	-0.35249	0.24414	0.61331*	0.15844	-0.01574
Nut weight	0.71094*	-0.43695	0.37599	0.06231	0.12058	-0.02185
Kernel weight	0.74613*	-0.34612	0.47473	0.05577	-0.00710	-0.00339
Kernel ratio	0.62319*	0.00408	0.60586*	0.02302	-0.35390	0.04423
Shell thickness	-0.53883*	-0.05205	-0.52489	0.11362	0.49324	-0.08428
Nut length	0.84033*	-0.04309	-0.29132	-0.05594	0.21680	0.36451
Nut width	0.77493*	-0.12639	-0.51640	0.09885	0.00962	0.19459
Nut thickness	0.72461*	-0.23794	-0.49863	0.22809	-0.22239	0.01464
Nut size	0.83237*	-0.14708	-0.47101	0.10259	-0.00738	0.19833
Kernel length	0.41561	0.83299*	0.01131	0.03147	-0.16552	0.22469
Kernel width	0.40766	0.88361*	0.04770	0.08680	-0.02483	0.00585
Kernel thickness	0.48584	0.83488*	-0.00898	0.15834	0.07061	-0.07507
Kernel size	0.45579	0.87726*	0.01593	0.10400	-0.02571	0.03360
Nut shape index	0.05053	0.24679	0.45079	-0.40919	0.58039*	0.44687
Kernel shape index	-0.30896	-0.54192*	-0.03101	-0.23386	-0.38525	0.52312*
Good kernel	0.84536*	-0.22042	-0.05218	-0.31447	0.06006	-0.21047
Wrinkled kernel	-0.80759*	0.03379	-0.04237	0.30917	-0.04578	0.21694
Empty kernel	-0.74461*	0.42155	0.14559	0.24791	-0.07078	0.13269
Double kernel	-0.43485*	-0.09427	0.08570	0.32303	0.00070	0.40617
Eigen value	7.54	4.21	2.25	1.28	1.10	1.03
% of variance	37.7	21.0	11.3	6.4	5.5	5.1
Cumulative	37.7	58.7	70.0	76.4	81.9	87.0

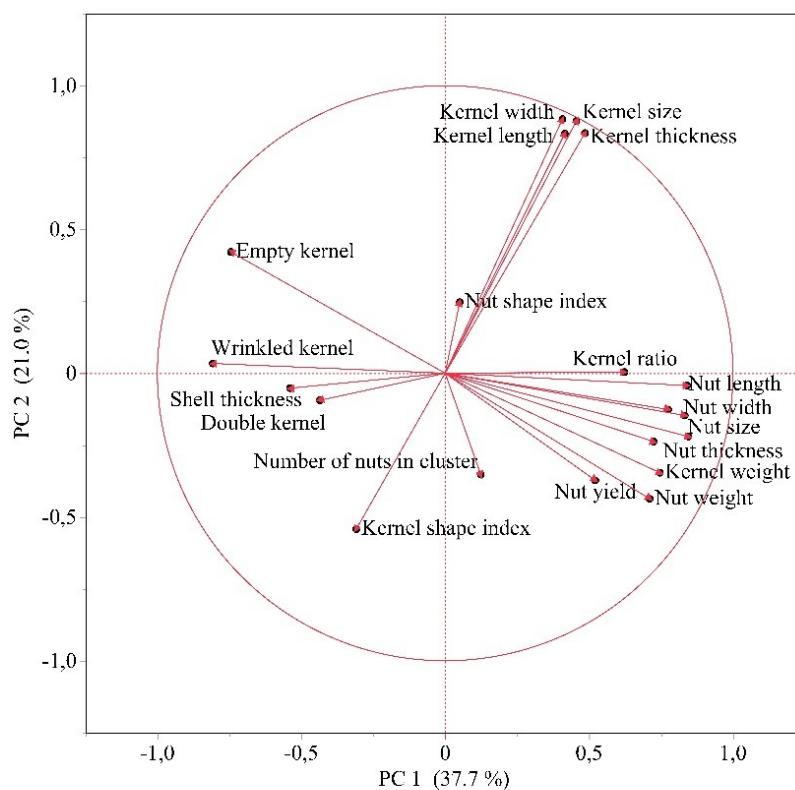
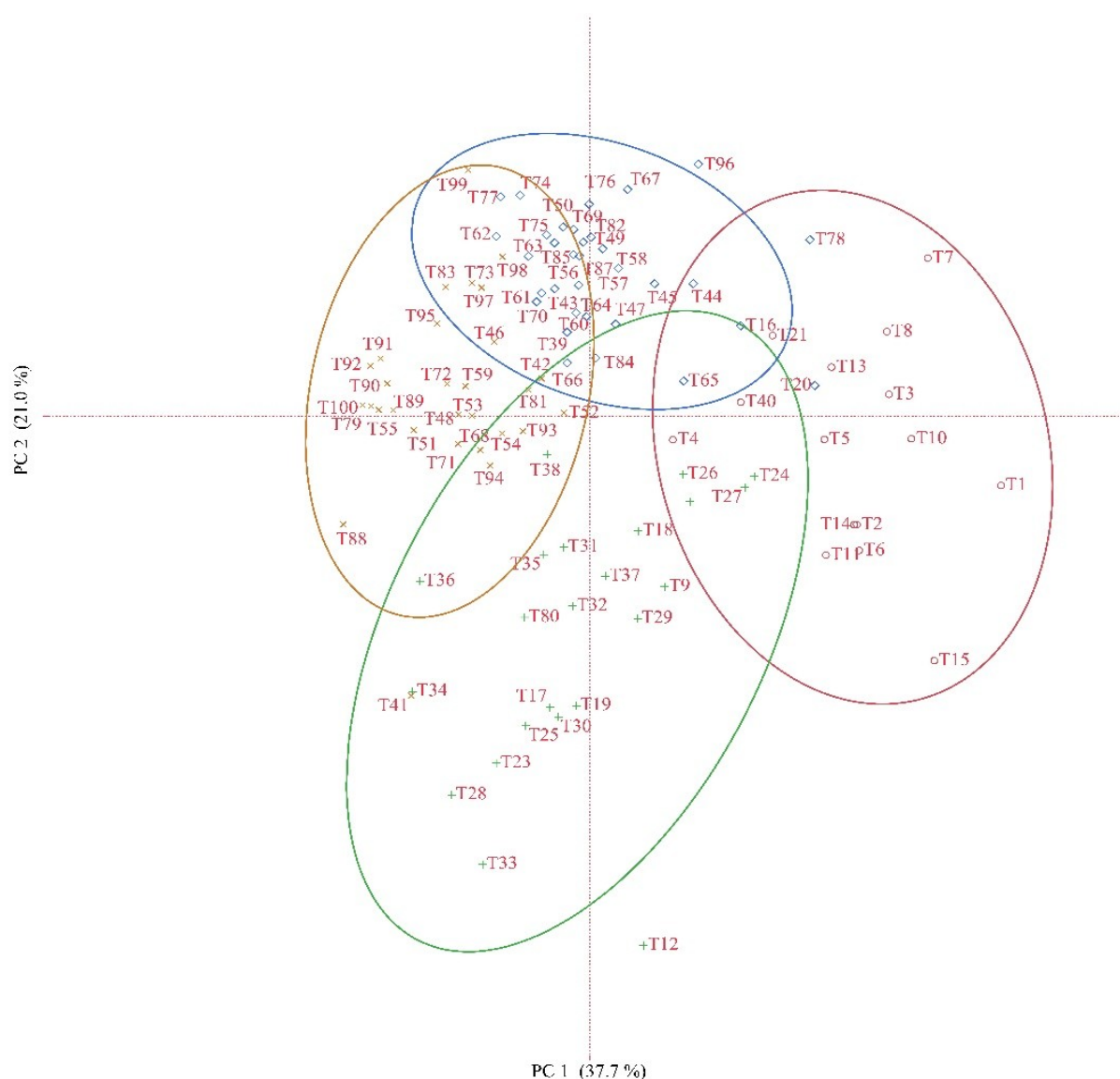
* Factor loading $\geq |0.43|$ are marked

Fig. 3: The plot of the first two PCA components of yield and nut traits of Tombul hazelnut clones



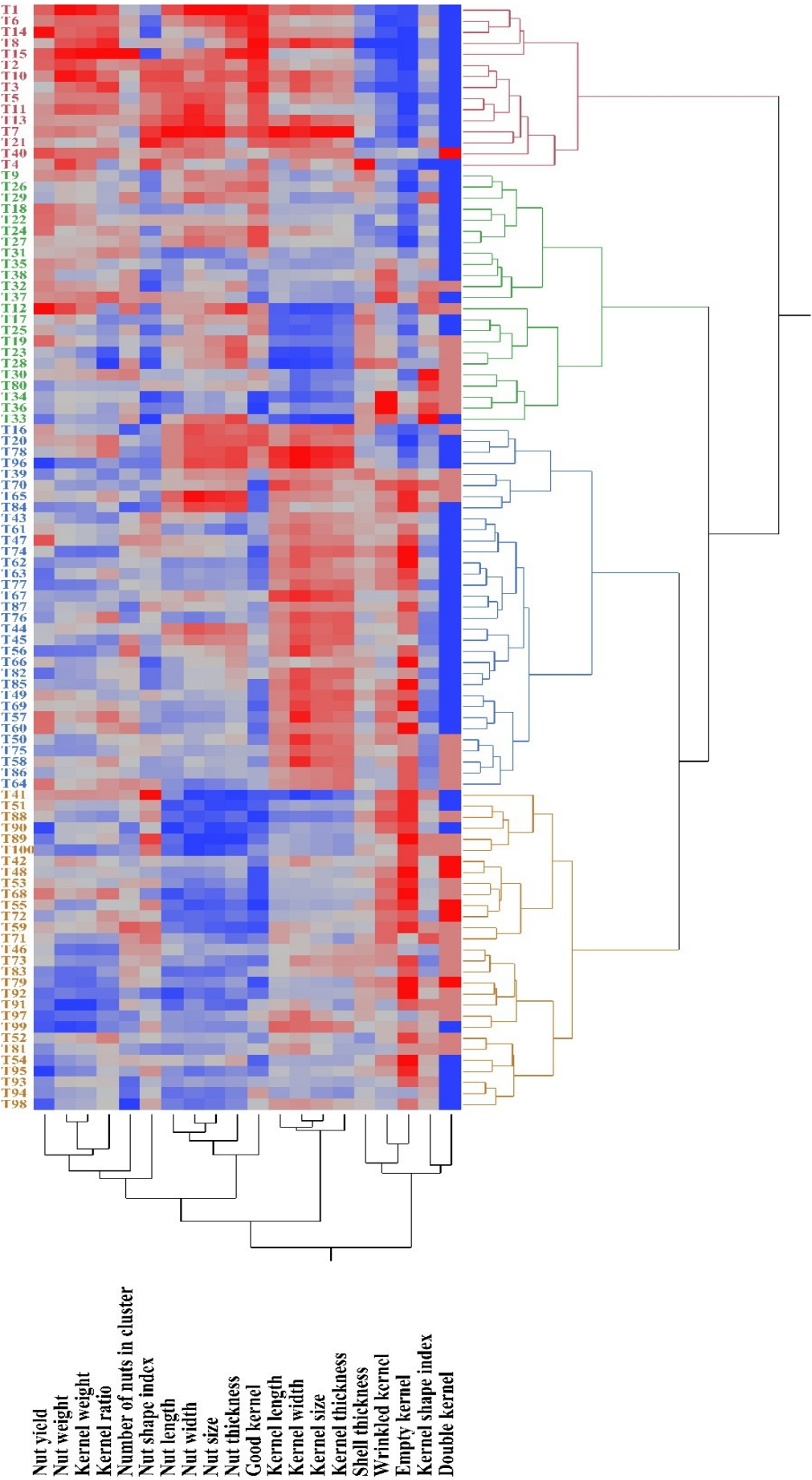


Fig. 5: Heatmap analysis and grouping of Tombul hazelnut clones based on yield and nut traits

A moderate positive correlation was detected among nut weight and nut yield ($r=0.69^{***}$). Nut weight showed a strong positive correlation with kernel weight ($r=0.97^{***}$). A high positive correlation was determined between kernel ratio and kernel weight ($r=0.79^{***}$). Kernel ratio showed a moderate positive correlation with nut weight ($r=0.63^{***}$). It also had a high negative correlation with shell thickness ($r=-0.76^{***}$). Nut size showed a strong positive correlation with nut dimensions (length, width and thickness) ($r=0.92^{***}$, $r=0.96^{***}$ and $r=0.91^{***}$, respectively). Nut dimensions showed a high positive correlation among themselves. Kernel size showed a strong positive correlation with kernel dimensions (length, width and thickness) ($r=0.96^{***}$, $r=0.98^{***}$ and $r=0.97^{***}$, respectively). Kernel dimensions showed a strong positive correlation among themselves. A high negative correlation

was determined between kernel shape index and kernel thickness ($r=-0.71^{***}$). Good kernel showed a strong negative correlation with wrinkled kernel ratio and empty kernel ratio ($r=-0.94^{***}$ and $r=-0.91^{***}$, respectively). It also had a moderate positive correlation with nut length, nut size, nut weight and kernel weight ($r=0.66^{***}$, $r=0.66^{***}$, $r=0.61^{***}$ and $r=0.61^{***}$). A high positive correlation was determined between wrinkled kernel ratio and empty kernel ratio ($r=0.72^{***}$). Empty kernel ratio showed a moderate negative correlation with nut dimensions (length, width, thickness and size) ($r=-0.63^{***}$, $r=-0.64^{***}$, $r=-0.60^{***}$, and $r=-0.67^{***}$ respectively) (Fig. 6). Many researchers have reported similar correlations between different hazelnut cultivars and clones (Islam et al., 2005; Petriccione et al., 2010; Bak and Karadeniz, 2021).

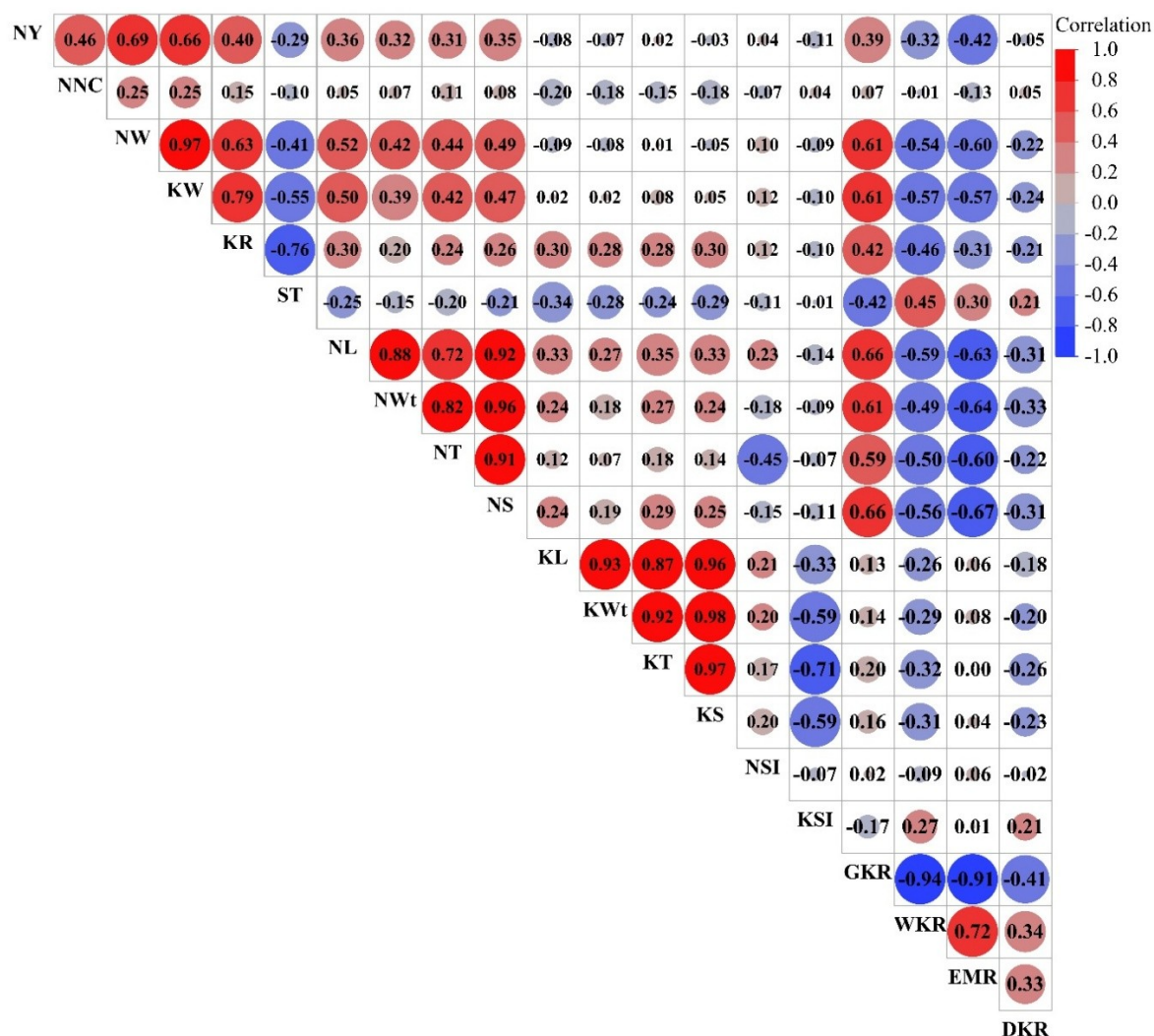


Fig. 6: Correlations among investigated traits of Tombul hazelnut clones

Conclusion

Considerable morphological diversity was detected among the investigated Tombul hazelnut clones, indicating a high diversity in population. This diversity enables the identification of individuals with superior productivity and nut quality, as well as resistant to diseases and pests, for hazelnut breeding programs. Furthermore, principal component analysis (PCA) demonstrated that the investigated traits effectively account for the morphological variation in hazelnut genetic resources. Among the clones investigated, T-12 and T-14 had remarkable yield, while T-1, T-10, and T-15 were superior in terms of important nut characteristics such as nut weight, kernel weight, kernel ratio, and good kernel. These clones exhibited promising morphological traits aligned with hazelnut breeders and growers. As a result of the pre-selection, these clones, characterized by significant morphological diversity, have the potential to be used as genetic resources in hazelnut breeding programs.

In addition, as hazelnut yield and nut traits are greatly influenced by environmental conditions, long-term studies spanning several years and conducted under the same ecological conditions will improve the evaluation of clone performance. Molecular characterization studies of the individuals under investigation are necessary to support clone identification and clarify the genetic basis of the observed variation. Furthermore, future studies integrating biochemical analyses—including antioxidant activity, phenolic compounds, fatty acid composition, oil and protein content—critical industrial parameters such as blanching ratio—will provide a more comprehensive basis for clone selection.

Author's contribution

FB: Investigation, methodology, conceptualization, data analysis, validation, supervision, writing – original draft, review and editing. **OK:** Data analysis, visualization, writing – original draft. **EP:** Investigation, data collections, visualization. **MFB:** Methodology, conceptualization, visualization, review and editing.

Conflicts of interest: The authors declare no conflict interest.

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Received February 3rd, 2026