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Fruit morphological and biochemical diversity in five Algerian pomegranate (*Punica granatum* L.) genotypes

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Abstract: Pomegranate (*Punica granatum* L.) is an ancient fruit linked to several cultures worldwide. It ranks as the second most valuable fruit crop in the Algerian Messaad region, after apricots, in terms of cultivated area, and is widely consumed in traditional dishes and juices, while being recognized for its therapeutic properties as a herbal remedy. Despite its importance, this fruit remains poorly studied in the region, with limited research addressing its productivity and characteristics. Local pomegranate genotypes possess distinct qualities that make them suitable for fresh consumption or processing. Therefore, evaluating local genotypes is essential to understand their physicochemical characteristics, nutritional composition, and potential contribution to the development of pomegranate cultivation and local agriculture. To achieve this goal, five pomegranate genotypes ('Hamraye', 'Snin Laâloudj', 'El Karess', 'Tounsi', and 'Khadraye') were evaluated based on laboratory analysis and the UPOV script to compare 27 fruit and seed parameters, including the physical characteristics of fruits, arils and seeds, and chemical properties of the juice, during two consecutive seasons (2023 and 2024). The studied genotypes revealed remarkable morphological and biochemical characteristics. The results showed that 'Snin Laâloudj' and 'Tounsi' had high sweetness (TS: 14.35 and 15.8 g 100 mL⁻¹), with a significant juice yield of 77.37 and 79.96%, respectively, together with a significant chemical composition, especially for 'Snin Laâloudj'. 'El Karess' is a unique cultivar with its sour-sweet taste (pH= 2.85), a significant juice yield of 71.28%, and a larger fruit and grain shape. However, 'Khadraye' and 'Hamraye' had the lowest values among the 27 studied variables. These findings demonstrate that local genotypes can provide valuable insights into the potential industrial use of 'Elkaress' and the nutritional applications of other genotypes.

1. Introduction

Pomegranate (*Punica granatum* L.) is an old and beloved plant and fruit. Recent studies have confirmed the traditional use of pomegranates as a medicinal remedy, as each part of this plant contains various chemical compounds (Holland *et al.*, 2009). It is also acknowledged as a vital commodity that is incredibly helpful in the human diet; its nutritional, therapeutic, and ornamental aspects have been known since antiquity (Liu *et al.*, 2025).

Wild pomegranates grow across Transcaucasia and Central Asia, from Iran and Turkmenistan to northern India (Chandra *et al.*, 2010; Shilpa *et al.*, 2024). As a result, it is considered to be indigenous to these regions. Since the pomegranate tree is extremely adaptable to a broad range of climatic and soil conditions, it has been planted in several tropical and subtropical environments (Yilmaz *et al.*, 2021). However, pomegranate is also widely cultivated in temperate regions and considered one of the best suitable areas for growing pomegranate like the Mediterranean climate (Beghè *et al.*, 2019). Interestingly, most of its cultivation is confined to the northern hemisphere, and the highest fruit quality is produced in arid lands (Rao, 2016). The plant is highly tolerant and resilient to poor soils, brackish water, and high altitudes (Rao, 2016). This makes the pomegranate tree a rustic species typical of temperate climates and is considered one of the most significant fruits of the restricted regions because of its low maintenance cost, significant yields, high preserving quality, and capacity to flourish with minimal moisture (Day and Wilkins, 2011; Ferrara *et al.*, 2021). Although this species is not very demanding and has the potential to expand and diversify fruit production, it receives less attention and is considered a neglected crop despite its economic, agronomic, and medicinal importance (Singh *et al.*, 2022).

Despite being assumed to have a restricted genetic base, pomegranates have a wide range of germplasm available globally, indicating great genetic diversity (Özgüven *et al.*, 2010). Although numerous countries have developed collections to conserve genetic material (Bartual *et al.*, 2025), the pomegranate remains a relatively understudied species on a national scale, despite its potential to improve and diversify fruit output in numerous parts of the world. In terms of genetic resources, there are many undetermined genotypes of pomegranates

characterized by diverse physicochemical qualities. In Algeria, pomegranate cultivation is important, where the cultivated area was estimated at 91578 ha to 93868 ha based on yield and production data (Meziane *et al.*, 2016). Although, the plantations are limited in Algeria. There are many genotypes of pomegranates, with very different qualities. Several genotypes are reported in small gardens in Kabylie such as Lahlou, and El-mouze, while numerous regions cultivate about 14 distinct genotypes, which are currently under production processes, such as Molla, Blanca, and Si Hueso (FAO, 2006). The fruit is popular for fresh consumption owing to its flavour and is widely grown, with the country's production contributing considerably to its economy. Moreover, studies are currently underway to evaluate the genetic diversity of Algerian pomegranate genotypes and their potential applications. However, in the Djelfa region, and more precisely in the commune of Messaad (Lahouel *et al.*, 2024). Several unstudied genotypes are highly appreciated in terms of taste quality, with an average yield ranging from 7.83 t ha⁻¹ to 8.42 t ha⁻¹ (Meziane *et al.*, 2016). Furthermore, the physical and chemical evaluation of pomegranates is crucial as it directly influences product morphology and fruit composition and is significantly affected by cultivar type (Asadi-Gharneh *et al.*, 2017). This evaluation and determination of different genetic resources also help identify genetic diversity and provides an opportunity for selection and fruit improvement programs.

Several prospecting visits were conducted to identify the pomegranate genotypes cultivated in the Messaad region, leading to the identification of five poorly documented local genotypes: 'Hamraye' (also known as 'Hamraoui'), 'Snin Laâloudj', 'El Karess', 'Tounsi', and 'Khadraye' ('Khadraoui'). These genotypes are traditionally grown in smallholder orchards and are locally consumed either fresh or as processed products; however, their physicochemical traits remain largely uncharacterized. Although the region possesses considerable pomegranate diversity, systematic scientific data on the fruit quality characteristics of these genotypes are limited to a few studies, except for the recent work of Lahouel *et al.* (2024) that include 3 out of our 5 chosen genotypes. While the initial study provided foundational insights, several genotypes remain unexplored, which this study could address through extending previous research by examining 2 more genotypes, and confirming the earlier conclusions as

well. On the other hand, missing study create a gap that limits their conservation, valorisation, and potential inclusion in breeding programs. Despite their local importance, a few comprehensive evaluations has been conducted to characterize the biochemical and morphologic attributes of these Messad's genotypes in the same study. Consequently, their comparative nutritional potential, quality, and suitability for fresh consumption or industrial processing remain insufficient. Hence, in this study it was hypothesized that these traditional genotypes exhibit significant variation in their physicochemical and biochemical fruit qualities, reflecting the underlying genetic diversity shaped by local agro-ecological conditions. Such variability may offer valuable traits for consumer preference targeting, breeding, and agro-industrial development of these species. Therefore, this study aims to: (1) characterize the physicochemical properties (e.g. fruit morphology, juice quality, and biochemical composition) of the five selected genotypes; (2) compare their quality profiles to identify distinctive traits of nutritional, agronomic, or industrial relevance; and (3) provide baseline data needed for genetic improvement programs, enhancement of local market value, and conservation strategies. By focusing on five little-known Messaad cultivars, this study offers original insights into the underexplored pomegranate diversity of the region and contributes valuable information to guide future food science, agricultural and industrial applications.

2. Materials and Methods

Site description

The study was conducted in the locality of Fayd Saaid in Messaad, south of Algiers. It is situated at coordinates 34°12'41'' N and 3°32'18'' E at an altitude of 798 m above sea level. The soil at the study site has a sandy-clayey-silty texture with a pH of 7.79. The average annual rainfall registered during the period from 2004 to 2024 was 314.95 mm for a mean rainfall duration of 68 days per year, and the average temperatures reached a maximum of 37 °C in July and a minimum of 2.8°C in January.

Planting materials and field conditions

The plant material evaluated consisted of five local genotypes Hamraye (HMR), Snin Laâloudj (SLL),

El Karess (EKS), Tounsi (TNS) and Khadraye (KDR) planted in an orchard of 3150 m², representing a total of 200 trees (40 trees for each genotype), planted together in 1995 at a spacing of 4.5 × 3.5 m. This spacing is not favourable for the vegetative growth of the species, which leads to difficulty in various cultivation operations (pruning, soil work, treatments, fertilization, and harvesting). Therefore, maintenance pruning (tree thinning) was performed once a year, considering the excess foliage generated by the tree to promote regular development. The orchard is irrigated at a yearly rate of 2500 m³ ha⁻¹ by a system of channels distributed from May to mid-October, a period where rainfall is less frequent as a complementary application based on the availability of pluviometry and replace the amount of water that crops need to replace water lost through evapotranspiration as highlighted by Volschenk (2020) which allows us to provide a mean value of 49.3 L for each tree per day based on plant requirement in a semi-arid condition (Meshram *et al.*, 2011). Fertilization was limited to organic manure in the summer period, and genotypes were distributed randomly in the same orchard, undergoing the same horticultural management practices according to recommendations for two main reasons: the traditional practice in the area and to improve soil quality characterized by a pH above 7 and low organic matter content.

Fruit sampling process

The optimal harvest time was determined based on visual and touching inspection, using a combination of objective, pre-defined criteria used locally including: skin colour, skin texture, fruit shape, calyx condition, easy fruit detachment and the acoustic response to tapping, all correlated against a pre-established calendar date range from first to mid-October 2023 and 2024, and then data from both years were pooled. Thus, following Williams *et al.* (2002), each tree was considered an experimental unit. Sampling was systematic, targeting 25 fully ripe fruits from multiple cardinal directions and vertical canopy heights (outer, mid, and inner canopy) on five representative trees to account for biological variability, we avoided fruits with visible damage, those that were most exposed to the sun, and those that were at the bottom of the tree. Regarding arils parameters, 50 arils per fruit were systematically taken from the top, middle, and bottom sections of the fruit and from different radial positions, then

mean was applied. Fruits were harvested manually at commercial maturity based on peel color development, fruit size, and total soluble solids stability. For each genotype, fruits were collected from five randomly selected trees, ensuring uniform exposure and excluding damaged or sunburned fruits. Twenty-five fruits per genotype per season were analysed. For seed and aril traits, measurements were performed on arils and seeds extracted from each fruit.

Fruits and seeds physical evaluation

The purpose of these measurements was conducted at the Biochemistry Laboratory (Faculty of Sciences, Yahia Fares University of Medea) to determine the size and dimensions of the collected fruits to highlight a distinction of the studied genotypes based on the guiding principles for conducting the examination of the distinctness and homogeneity provided by the UPOV script available online (UPOV, 2013). A total of nine parameters were evaluated using 25 fruits: Fruit weight in g (FW), average number of arils per fruit (NAF), average length of fruits (FL) in mm, average width of fruits (FT) in mm, average thickness of the peel (PT) in mm, weigh of peel and husk after separation of the edible part per fruit (PHW) in g, total weight of arils in g for each fruit (TAW), average width of the calyx (CT) in mm and average length of the calyx (CL) in mm. In addition to 6 physical properties of arils and seeds including: average length of arils (AL) in mm, average width of arils (AT) in mm, average seed weight (SW) in g, average width of seeds (ST) in mm, average length of seeds (SL) in mm and average weight of arils (AW) in grams.

Fruits biochemical analyses

To determine the main chemical components, we also used laboratory testing protocols, such as the volume of juice in millilitres 100 g⁻¹ of arils (JY). Juice was extracted from the arils using a manual press and filtered through a nylon mesh, followed by the measurement of fruit water percentage (FWP) and dry matter weight (DMW) in grams. The dry matter rate (DMR) was then estimated as a percentage (g per 100 g of fresh matter). The samples were kept at 4°C in the dark for later analysis of total soluble solids content (TSS) using a digital refractometer (Atago N1, Tokyo, Japan), and the results were reported as °Brix at 20°C. The pH was measured using a digital pH meter (Metrohm model 601) at 21°C. The titratable

acidity (TA) was determined by titrating 10 mL of juice with 0.1 N NaOH solution to pH 8.1 and expressed as grams of citric acid per 100 mL of juice (Tyl and Sadler, 2017). The maturity index (MI) was generated based on the ratio of TSS to TA, as suggested by Martínez *et al.* (2006). Vitamin C or ascorbic acid concentration (AA) was determined in triplicate using a colorimetric method with some modifications as described by Arendse *et al.* (2014), expressed as mg 100 mL⁻¹. The total protein (TP) content in dry pomegranate pulp was determined in g 100 mL⁻¹ according to the Folin phenol reagent method described by Meziane *et al.* (2016). The total sugar content (TS) was calculated in g 100 mL⁻¹ using the method described by Dubois *et al.* (1956). Juice pulp (JP) was estimated in grams of pulp per 100 mL of pure juice according to Barkhatov and Elisseev (1979).

Statistical analysis

Data were analyzed statistically through analysis of variance (One-Way ANOVA) using R software (version 4.1.1). The homoscedasticity was verified with the test of pairwise Mean comparisons were performed using Fisher's least significant difference test at $\alpha = 0.05$. Principal component analysis (PCA) was performed to explore relationships among variables and to reduce data dimensionality. Prior to analysis, data were standardized to eliminate scale effects (mean= 0, SD= 1), PCA was conducted on the correlation matrix, and principal components were retained based on cumulative explained variance, with the selected components accounting for at least 70% of the total variance. Finally, clustering was performed using the Euclidean distance and Ward's method of linkage.

3. Results

Pomological-based characterization of pomegranate genotypes

For all the physical variables of the fruits, the results showed strong fluctuations in values with respect to the studied genotypes, whose fruits have diverse shapes and dimensions. However, it should be noted that there is no significant difference between the recorded means of the peel thickness ($p > 0.05$). Accordingly, the statistical test showed homogeneity of variance, and the physical characterization of the fruits according to the

analysis of variance showed a significant difference for all physical parameters (p-value less than 0.05), except for peel thickness (PT), where it was not significant (p-value > 5%) (Table 1). Based on means comparisons, the average FW varied between a minimum of 156.40 g for HMR genotype (group “a”) and a maximum value of 249.11 g for EKS (group “b”), reflecting a marked genetic influence on fruit size. The highest PHW were recorded in EKS (99.46 g), whereas the lowest were observed in SLL (66.64 g). However, the TAW ranged from the lowest value of 84.35 g, HMR to the highest mean of 150.44 g EKS in this study. The comparison test also revealed notable differences in fruit dimensions: in term of fruit length genotype TNS recorded the highest mean value (67.12 mm), whereas HMR exhibited the lowest value (57.82), whereas regarding the fruit width, HMR belonged to the highest significance group, while SLL was classified in the lowest group, ranging from 66.0 mm to 75.36 mm respectively. The CL results showed that several genotypes shared the

highest statistical group, including KDR, SLL and TNS, while EKS was grouped among the lowest. While the calyx diameter the highest mean value was observed in genotype SLL, while the lowest was recorded in genotype EKS and KDR, with values ranging between 15.64 mm and 18.24 mm.

Seed and aril-based characterization of pomegranate genotypes

The physical variables of the seeds presented average outputs with remarkable variations among the studied genotypes, and their seeds were of different shapes and sizes. Statistically, the analyses of variance showed a significant difference among the seed variables of the genotypes (p-value < 5%) (Table 2). The average AW of the examined genotypes ranged from 0.41 g for EKS to 0.32 g for HMR and KDR. Moreover, the average SW is an indicator of its quality. Hence, our investigated cultivars, EKS and KDR, have the highest SW with 0.045 g and 0.042 g (group “b”), respectively, while

Table 1 - Physical characterization of the five genotypes fruits associated with their means and standard deviation

Parameters	Genotypes					p-value
	El Karess	Hamraye	Khadraye	Snin Laâloudj	Tounsi	
Peel thickness (mm)	2.42±0.095 a	2.24±0.082 a	2.12±0.082 a	2.34±0.087 a	2.18±0.079 a	0.09355 ns
Fruit weight (g)	249.12±20.16 b	156.40±9.12 a	195.65±15.76 ab	197.16±16.94 ab	209.51±13.82 ab	0.001887 **
Fruit length (mm)	66.02±1.92 b	57.82±1.27 a	63.29±1.23 ab	64.64±1.52 b	67.12±1.15 b	0.0001286 ***
Fruit width (mm)	74.68±2.22 b	66.02±1.41 a	69.91±1.49 ab	75.36±1.83 b	72.20±1.74 ab	0.001568 **
Calyx length (mm)	18.53±0.52 b	16.19±0.69 ab	14.86±0.61 a	14.24±0.64 a	15.89±0.74 a	0.0009214 ***
Calyx width (mm)	15.11±0.53 a	17.12±0.60 ab	15.64±0.44 a	18.24±0.46 b	16.42±0.71 ab	0.001089 **
Number of arils per fruit	364.32±18.80 bc	230.14±10.04 a	417.84±16.38 cd	295.28±21.32 ab	469.16±25.31 d	5.019e-15 ***
Total aril weight per fruit (g)	150.44±11.93 b	84.35±4.97 a	129.47±11.40 b	130.52±10.61 b	138.09±8.89 b	0.000103 ***
Peel (husk) weight per fruit (g)	99.46±10.07 b	72.05±6.76 ab	70.58±8.71 ab	66.64±7.62 a	71.42±5.85 ab	0.02947 *

Values represent mean ± standard deviation (SD). Different letters indicate significant differences among genotypes for each trait : ***Very highly significant, **Highly significant, *Significant, ns: non-significant (p-value > 0.05). Statistical analysis was determined using One-Way ANOVA.

Table 2 - Physical characterization of the five genotypes seeds associated with their means and standard deviation

Parameters	Genotypes					p-value
	El Karess	Hamraye	Khadraye	Snin Laâloudj	Tounsi	
Seed weight (g)	0.045±0.003 b	0.03±0.001 a	0.042±0.002 b	0.026±0.0013 a	0.028±0.0014 a	2.49e-12 ***
Seed length (mm)	8.65±0.20 c	5.97±0.13 a	6.76±0.088 b	6.56±0.199 ab	6.16±0.117 a	< 2.2e-16 ***
Seed width (mm)	3.15±0.11 b	2.71±0.073 a	2.78±0.102 a	2.97±0.065 ab	2.97±0.098 ab	0.00754 **
Aril weight (g)	0.41±0.018 b	0.32±0.011 a	0.33±0.013 a	0.395±0.013 b	0.386±0.012 b	0.000005014 ***
Aril length (mm)	12.42±0.28 b	10.52±0.19 a	10.47±0.201 a	11.28±0.176 a	11.34±0.236 a	0.0000000094
Aril width (mm)	7.53±0.12 ab	7.43±0.17 ab	7.30±0.207 a	8.11±0.152 b	7.91±0.227 ab	0.008921 **

Values represent mean ± standard deviation (SD). Different letters indicate significant differences among genotypes for each trait : ***Very highly significant, **Highly significant, *Significant, ns: non-significant (p-value > 0.05). Statistical analysis was determined using One-Way ANOVA.

the TNS, SLL and HMR genotypes possess the lowest SW with 0.02 g, 0.026 g and 0.03 g respectively (group “a”). The KDR and HMR genotypes had the smallest AL (10.47 mm and 10.52 mm, respectively), whereas the EKS genotype had the largest AL (12.42 mm), The test revealed that EKS (group “b”) significantly outperformed all other genotypes that showed the poorest performance (group “a”). Furthermore, the ANOVA test showed a significant difference for the seed dimensions of the EKS genotype (length 8.65 mm, width 3.15 mm) was significantly higher than the remaining genotypes, while genotype HMR (length 6.16 mm, width 2.71 mm) was significantly lower.

Biochemical-based characterization of pomegranate genotypes

A large variability was observed in the chemical parameters of the fruits, with remarkable deviations in the recorded means. The test showed homogeneity of variance, and all the biochemical parameters showed highly significant variability between the studied genotypes, as indicated by the analysis of variance (p-value < 5%) (Table 3).

Multivariate approach to characterize pomegranate genotypes

Principal component analysis allowed us to establish a link between the treated physicochemical parameters. The first two axes (also known as the first plan) presented a total inertia rate of 75.27%

(Fig. 1). Thus, the first group of variables was positively correlated and explained a strong relationship between SL, CL, SW, PHW, and DMW, which characterized the unique EKS genotype. This genotype also registered a higher value of the second group, especially for the first dimension (47.91%) for JP, NAF, total protein content, FL, FT, AW, DMR, TAW, ST, AL, FW, and PT. Both KDR and HMR individual are distributed in this group (Fig. 1 and 2). Moreover, a strong positive correlation was observed

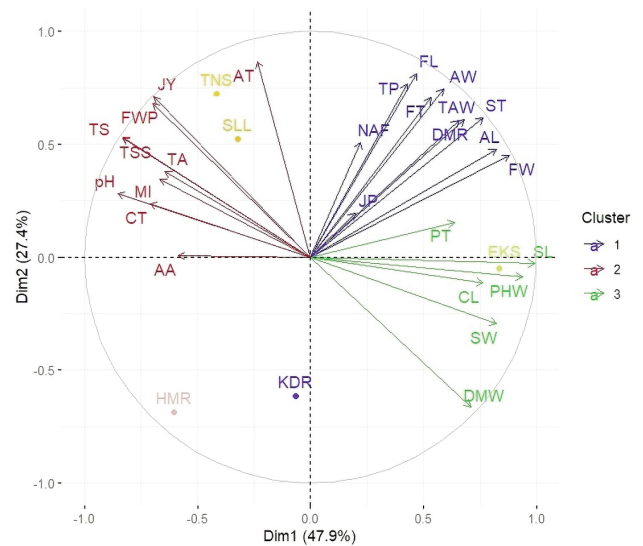


Fig. 1 - Dimension reduction plot showing the distribution of variables and individuals on the first component, which explains 75.27% of the total variance; using Principal Component Analysis (PCA).

Table 3 - Chemical characteristics of the five genotypes fruits associated with their means and standard deviation

Parameters	Genotypes					p-value
	El Karess	Hamraye	Khadraye	Snin Laàloudj	Tounsi	
Juice yield (%)	71.28±0.48 a	74.91±0.89 b	73.27±0.46 ab	77.37±0.58 c	79.96±0.62 d	< 2.2e-16 ***
Fruit water percentage ((%)	79.79±0.302 a	81.47±0.501 ab	80.87±0.23 ab	82.23±0.49 bc	83.85±0.59 c	0.000000047 ***
dry matter weight (g)	20.20±0.303 c	18.44±0.499 b	19.12±0.236 bc	17.77±0.49 ab	16.15±0.59 a	0.000000048 ***
pH	2.85±0.036 a	3.89±0.041 c	3.44±0.023 b	4.35±0.049 d	3.81±0.029 c	< 2.2e-16 ***
Titrateable acidity (%)	0.34±0.005 a	0.38±0.005 b	0.34±0.007 a	0.41±0.005 c	0.37±0.004 b	< 2.2e-16 ***
Dry matter rate per fresh matter (%)	0.34±0.007 e	0.24±0.004 b	0.22±0.005 a	0.27±0.005 c	0.30±0.005 d	< 2.2e-16 ***
Total protein (g)	1.29±0.034 c	0.72±0.030 a	1.01±0.029 ab	0.99±0.029 ab	1.49±0.04 d	< 2.2e-16 ***
Juice pulp (g)	1.41±0.0072c	1.19±0.006 a	1.64±0.008 e	1.28±0.014 b	1.55±0.011 d	< 2.2e-16 ***
Total soluble solids (°Brix)	11.67±0.178 a	14.97±0.087 c	13.56±0.089 b	15.40±0.081 c	17.05±0.097 d	< 2.2e-16 ***
Maturity index	34.41±0.546 a	40.19±0.59 c	39.76±0.72 c	37.17±0.45 b	45.87±0.43 d	< 2.2e-16 ***
Vitamin C (mg)	8.60±0.098 a	11.67±0.073 c	13.70±0.081 d	9.55±0.052 b	13.99±0.08 d	< 2.2e-16 ***
Total sugar (g)	10.79±0.164 a	13.87±0.082 c	12.55±0.090 b	14.35±0.105 d	15.80±0.091 e	< 2.2e-16 ***

Values represent mean ± standard deviation (SD). Different letters indicate significant differences among genotypes for each trait : ***Very highly significant, **Highly significant, *Significant, NS: non-significant (p-value > 0.05). Statistical analysis was determined using One-Way ANOVA.

between AA, CT, maturity index, pH, TA, TSS, TS, FWP, JY, AT, which characterized the TNS and SLL genotypes as a third group (Fig. 1 and 2). The latter were negatively correlated with the former (Fig. 1).

4. Discussion and Conclusions

Physical assessment is considered an important trait for distinguishing cultivars (Radunić *et al.*, 2024) and is easy to evaluate, offering a better description and genetic diversity comparison. Physical analysis revealed remarkable differences in the characteristics of Algerian pomegranate genotypes. These valuable yet overlooked fruits come from a rich genetic pool.

In this work, the PT was the only variable that revealed no significant difference among cultivars; conversely, fruit weight showed significant differences between cultivars. EKS pomegranate is the heaviest, while HMR weighs the least. These results are comparable to those reported by Beghè *et al.* (2024) for some Italian cultivars and Meziane *et al.* (2016) for some Algerian cultivars, confirming that fruit weight is strongly cultivar-dependent. Based on the classification proposed by Martínez-Nicolás *et al.* (2006) for Spanish cultivars, all studied genotypes can be classified as medium to large fruits (150-350 g). However, the inner thick spongy white tissue and the outer smooth skin layer constitute the peel (da Silva *et al.*, 2013). When measured, it indicates the proportion of inedible part per fruit (PHW), which differs from one cultivar to another, giving a juice

transformation disadvantage to cultivars such as EKS but offering an opportunity to provide a particularly high peel natural source of nutritional, therapeutic, and industrial compounds, as highlighted by Kanatt *et al.* (2010). This increased interest in peel thickness, even if consumers generally prefer pomegranate fruit with a thin peel because they have reduced fruit waste and are easy to peel (Radunić *et al.*, 2015), indicates potential health benefits.

The length and width attributes of the fruits measure the fruit size and express variable values (Wetzstein *et al.*, 2013), which exhibit considerable phenotypic diversity in fruit size among the five genotypes. This revealed that TNS and KDR were more spherical (oblate spheroid) and the remaining three genotypes were more elongated (ellipsoid), similar to the mass modelling provided by Khoshnam *et al.* (2007) confirming that fruit shape varies according to genotype and has implications for the market and industrial processing. Accordingly, most cultivars have round shapes, but our genotypes have an angular form, except that SLL presents a distinct smooth shape. Similarly, HMR, TNS, and KDR have a rounded calyx, whereas genotypes such as EKS and SLL possess an elongated calyx. These results are in line with those reported for other pomegranate genotypes by Fawole and Opara (2013) and Shi (2025).

The arils are the edible portion of pomegranate fruit, containing the juice, the pulp and the seeds. Thus, knowing these characteristics enable producers and processors to promote this fruit better (Meziane *et al.*, 2016). The number of arils per fruit increased in accessions HMR and TNS respectively. These results reflect the combined influence of genetic and environmental factors and are comparable to those reported by Hmid (2013), while remaining consistent with Radunić *et al.* (2015) and Rajkumar *et al.* (2020), highlighting the role of genotype and fertilization in aril yield. In addition, several studies have shown that pollen sources can also modify the number, size, and weight of arils (Gharaghani *et al.*, 2017). Furthermore, certain physical properties of the fruit, such as mass and volume, can indicate the potential number of arils (Çelik and Ercisli, 2009). Moreover, the aril weight was higher for EKS, SLL, and TNS genotypes and weak for the other two accessions, similar to seed sizes, which may influence consumer preference and suitability for industrial processing (Chandra *et al.*, 2013). None of the genotypes were

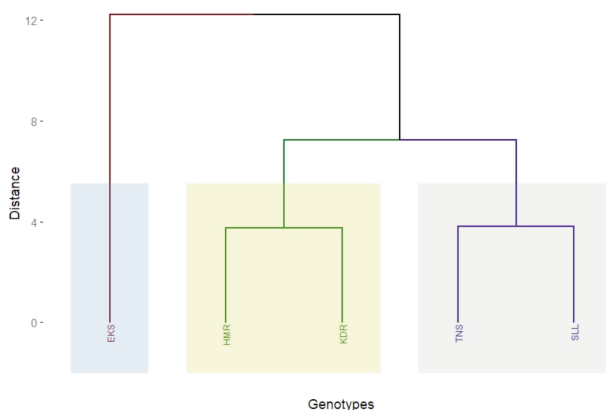


Fig. 2 - Dendrogram showing three clusters based on the distances among the pomegranate genotypes studied using the Euclidean distance and Ward's method of linkage.

seedless; as a result, larger seed weights were associated with EKS and KDR accessions. However, the other genotypes are more appreciated for direct consumption due to low SW. This could be a result of genotype characteristics and/or cross-pollination, which often causes increased fruit set and fruit and AW, all of which improve the yield and quality of this fruit crop (Derin and Sinan, 2001), as our genotypes were planted in the same orchard. In addition, the same author recommends planting at least two different cultivars of pomegranates in an orchard to encourage pollination and optimal fruit set.

Analysis of the essential components of five overlooked Algerian pomegranate genotypes revealed clear patterns in their fruit quality. Pomegranate juice is a rich source of dietary nutrients and bioactive compounds with potential therapeutic effects (Hegazi *et al.*, 2021). In addition to medicinal quality, the juice yield varied from genotypes to another, with the TNS genotype exhibiting the highest yield. This is higher than the yields reported by Lahouel *et al.* (2024) and by other genotypes studied in the wet area of Boufarik (Meziane *et al.*, 2016) and is comparable to the values reported by Radunić *et al.* (2015) and Zaouay and Mars (2011). High juice yield is a critical factor in the juice industry, as it directly impacts the economic viability of processing operations (Taylor, 2004). The differences in juice yield among the genotypes can be attributed to genetic factors and growing conditions (Li *et al.*, 2015). Genotypes with higher juice yields, such as TNS and SLL, are particularly valuable for industrial applications, where maximizing the volume of juice extracted is essential. This is associated with the FWP, dry matter weight and ratio (DMW, DMR), and the TSS, since water is the essential component of juice and the dry matter reflects the juice concentration that could be affected by water availability. As mentioned by Adiba *et al.* (2022), water stress could not only affect juice yield but also the quality of juice. Accordingly, the water content per fruit of genotypes was inferior in EKS and superior in TNS. This characteristic depends on climatic factors and the irrigation regime during critical phases. The results are comparable to those reported by Hmid (2013) for other pomegranate genotypes, confirming the influence of genetic and environmental factors on juice yield and quality.

The pH levels varied significantly among the genotypes. SLL exhibited the highest pH, while EKS, a

local variety known for its acidic taste showed an acidic profile. Moreover, these pH results were generally lower than those reported by Assadi *et al.* (2019), except for SLL genotype. Similarly, compared with the findings of Lahouel *et al.* (2024) in the Messaad region, lower pH values were recorded HMR, KDR, and TNS, whereas Snin Laâloudj displayed comparable values in both studies. Furthermore, the pH values for EKS genotype were consistent with those reported by Elfazazi *et al.* (2022) for other genotype such as Acco I genotype. These differences may result from intra-cultivar variation, fruit maturity, and environmental or cultural factors. In addition to the impact of genotype, temperature and storage conditions can affect juice pH (Darvishi, 2013). Consequently, the titratable acidity also differed significantly among cultivars; SLL had the highest acidity, while EKS showed the lowest, which is consistent with the values reported by Lahouel *et al.* (2024). These acidity levels are comparable to those reported for Spanish genotypes and Tunisian cultivars (Zaouay *et al.*, 2012; Alcaraz-Mármol *et al.*, 2017). Although Assadi *et al.* (2019) reported higher acidity value. However, excessively high acidity may require adjustments during processing to achieve the desired flavour profile.

Regarding protein, pulp, sugar, and AA contents, the TNS and SLL genotypes had higher values than the other genotypes, demonstrating the nutritional importance of this genotype, alongside a higher maturity index, which is a vital indicator of fruit quality and important in maintaining high total component content (Fawole and Opara, 2013). The values observed are close to those of the Kashmir genotypes (Wani *et al.*, 2012) and consistent with Lahouel *et al.* (2024).

The total soluble solids (TSS) content of juice increases with maturity (Mohamed *et al.*, 2015; Kumar and Gill, 2017). Our results suggest that the TNS genotype had the highest Brix value, while the EKS genotype had the lowest. The values for SLL and HMR were similar, in agreement with Lahouel *et al.* (2024) and Beghè *et al.* (2024) for other genotypes. Furthermore, regional climatic conditions, such as temperature and humidity, have an important impact on determining TSS levels, with Mediterranean regions create greater TSS values than in desert climate (Schwartz *et al.*, 2009). Accordingly, Mphahlele (2016) found that genotype-specific variables had the greatest effect on the sugar profiles

of pomegranates.

In terms of vitamin C content, the TNS genotype juice had the highest concentration, followed by KDR and HMR. The EKS genotype had the lowest AA content. AA levels were greater than those reported by Tehranifar *et al.* (2010) and Ferrara *et al.* (2011). Previous studies show that high concentrations of AA are associated with strong antioxidant potential (Ramezani *et al.*, 2010). Variability in soil conditions may affect the chemical composition of pomegranates (Hassen *et al.*, 2021).

According to the data, the protein content varied by genotype, with the highest value expressed by TNS. The protein content of the juice was comparable to the values reported by Hmid (2013) and Meziane *et al.* (2016). As demonstrated by Hassen *et al.* (2021), soil type significantly affects protein accumulation in harvested fruits.

Pomegranate juice pulp is a vital dietary component. It contains substantial sugars and minerals such as potassium, magnesium, and calcium, which support various physiological functions and enhance the nutritional value of the fruit (Elfalleh *et al.*, 2011). The finding in this study reports that the KDR and TNS genotypes had the highest pulp content in juice, while the HMR genotype had the lowest value. Although the extraction process may impact pulp concentration.

According to SaeiAhagh *et al.* (2015), increased aril weight and volume exert higher internal pressure inside fruits, which can lead to cracks inside the peel and consequently affect the pulp yield. In addition, fruit shape and skin thickness play a crucial role in cracking susceptibility. Weather conditions, such as temperature and humidity, significantly affect the rate of fruit cracking, which can reduce the composition and quality characteristics of the yield (Singh *et al.*, 2020). Different pollen sources can lead to variations in fruit set rates and overall fruit quality, thereby affecting pulp yield (Gharaghani *et al.*, 2017). Pre- and post-harvest handling: Practices such as irrigation, fertilization, and post-harvest treatments can enhance the bioactive compounds in the pulp, thereby improving its quality (Mphahlele, 2016). However, while these elements typically increase pulp output, extreme environmental stress or poor agricultural techniques might result in inferior fruit quality and pulp levels, which emphasizes the importance of balanced cropping strategies.

Principal Component Analysis (PCA) identified an evident pattern in the various characteristics.

Therefore, we chose to proceed using the first two dimensions, revealing several key relationships, and a variable correlation exists between the three previously mentioned groups. Variable distribution analysis revealed significant relationships between several physicochemical parameters. For instance, a positive correlation was observed between each group; CL was highly associated with PHW, and genotypes holding those parameters possessed long SL that weighed more SW, resulting in a higher dry matter (DMW). This is slightly negative for the second group, especially in the second dimension, which is in harmony with the findings of Zarei *et al.* (2011), where ripe fruit had the maximum amount of aril and juice, but the lowest percentage of peel and seed. However, the TAW is more affected by the NAF, ST, AW, and AL. In addition, JY is associated with fruit size (FL and FT), which results in a higher FW, DMR, TP, and JP. Moreover, the PT was situated between these groups, suggesting its contribution to both groups. The present results oscillated around the mean values reported by Dhineshkumar *et al.* (2015) for average fruit mass, length, and width. Consequently, increasing the overall aril weight resulted in higher juice production (Radunić *et al.*, 2024), which is consistent with the findings of the current study.

A negative correlation appeared between the first two groups and the third group, showing a high interaction among the remaining eight variables, including FWP, which contains a higher TSS, AA, total sugar content, juice pH, and titratable acidity, all of which offer an interesting maturity index (MI) and are characterized by a large CT and AT. Similarly, fruit and aril size decreased, with reduced total soluble solids and acidity, when exposed to low nitrogen fertilization (Lyu *et al.*, 2020), their results indicated that soluble solids content, juice pH, total sugars, and AA levels in the juice were abundant. These findings provide insights into the changes in the physical and chemical properties of pomegranate fruits during maturation (Erkan and Kader, 2011).

Consequently, KDR and HMR genotypes hold lower values for these variables, and EKS is considered a better fruit for industrial purposes, producing more JY and a lower pH that could be adjusted within the transformation process and a thick peel that may hold significant importance in medicine purposes. Moreover, TNS and SLL contain smaller seeds which give them an advantage in the market and are more appreciated in direct

consumption as fresh fruit.

This study demonstrated significant physico-chemical variability among five Algerian pomegranate genotypes cultivated in the Messaad region, reflecting clear genotype-dependent differences in fruit quality traits. TNS and SLL were particularly suitable for fresh consumption due to their higher sweetness, whereas EKS showed strong potential for industrial processing owing to its larger fruit size and thicker peel. Similarities were observed between KDR and HMR, while EKS exhibited a distinct physico-chemical profile. Although the results are based on a limited number of genotypes and growing seasons, they provide valuable insight into the characterization and valorization of local pomegranate genetic resources. Further multisite and multiyear studies are recommended to strengthen the understanding of genotype environment interactions and to support their optimized use for fresh consumption and processing.

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