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THE INFLUENCE OF PARENTS ON PULP FIRMNESS AND KEEPING THE CAPACITY IN APPLE GENOTYPES

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Abstract

The aim of the study was to evaluate the influence of parents on the expression of pulp firmness, a morpho-physiological trait essential for the quality and keeping capacity of apple fruits. The research also sought to highlight the genetic contribution of different parental combinations to both the level and stability of this trait in order to identify valuable parents for breeding programs. The results revealed a significant phenotypic variability in pulp firmness among the 40 genotypes analyzed, as well as interannual differences determined by the genotype–environment interaction. Certain parental combinations, particularly those including the parent 'Prima', were frequently associated with high and stable firmness values, both at harvest and after storage. Moreover, the concordance between non-destructive and destructive evaluation methods confirms the efficiency of rapid firmness assessment in genotype selection. Overall, the findings underline the determining role of genetic background in firmness expression and the importance of careful parent selection for developing varieties with stable texture and superior storage capacity.

Key words*: apple, fruit firmness, parental influence, genotype-environment interaction.*

INTRODUCTION

The quality of apple fruit (*Malus domestica* Borkh.) is determined by a complex of genetic, physiological, and environmental factors; among which pulp firmness, skin thickness, and the presence of the waxy layer play an essential role in mechanical resistance, tolerance to pathogens, and storage behaviour (Iancu et al., 2023). The importance of firmness as the main indicator of commercial quality and storage capacity has been emphasized in numerous specialized works. Firmness is the main technological criterion for differentiating batches intended for long-term storage from those for rapid consumption (Goncalves et al., 2017). Firmness was included as an essential parameter in the overall quality index (OQi) model, along with acidity, demonstrating a direct correlation with sensory scores for overall quality (Ahmad et al., 2021). The results of a study conducted by Djekic et al. (2019) show that the notion of quality evolves along the value chain, from production parameters to internal sensory characteristics, confirming the importance of firmness and texture as essential elements in the consumer's perception of quality. Also, the results obtained by Hardner et al. (2016) on genetic variation and correlations between instrumental and sensory firmness support the importance of firmness as a relevant heritable character for selection and for predicting the performance of new cultivars in breeding programs. The structure and composition of the superficial tissues of the fruit, especially the cuticle, significantly influence the postharvest storage potential, acting as a barrier against water loss, chemical aggression, mechanical damage, and microbial infections (Lara et al., 2014). Existing literature indicates that cuticle properties are correlated with loss of firmness and susceptibility to physical and biological stress, highlighting its role as a determinant of quality and storage behaviour. Although the physiological mechanisms of softening have been intensively studied, the variation in firmness observed in the market remains insufficiently explained, which makes it difficult to effectively manage fruit texture in the commercial chain (Johnston et al.,

2002). In the context of climate change and increasingly stringent market requirements regarding quality and shelf life, the identification of parents capable of transmitting these traits at high frequency is becoming a priority direction in apple breeding (ECPGR, 2022; Militaru et al., 2021; Gavrilă et al., 2025). Modern breeding strategies aim to integrate quality traits with resistance to biotic and abiotic factors in order to obtain varieties adapted to new pedoclimatic conditions and the requirements of the storage and marketing chain. The study by Morariu et al. (2025) shows that genotype and growing conditions significantly influence apple production and quality, highlighting the genotype-environment interaction and the importance of integrating genetic and agronomic factors in breeding and management. Studies have shown that firmness is closely related to cell wall structure, pectin composition, and degradation, as well as the activity of enzymes involved in the ripening process (Brummell & Harpster, 2001; Johnston et al., 2002; Li et al., 2026). At the same time, the thickness of the epidermis and the characteristics of the waxy layer contribute to reducing water loss, limiting microcracks, and mechanically protecting the fruit during handling and storage (Lara et al., 2014). However, the relationships between these traits, their correlations, and genetic determinism remain insufficiently clarified, especially in the specific pedoclimatic conditions of Romania, where the genotype × environment interaction can significantly influence the phenotypic expression of quality traits. The aim of the work was to evaluate the influence of parents on the expression of pulp firmness, as a morpho-physiological character essential for the quality and keeping capacity of apple fruits. The study aimed to highlight the genetic contribution of different parental combinations to the stability and level of this character, in order to identify valuable parents for breeding programs.

MATERIALS AND METHODS

Biologic materials

The biological material studied was represented by 40 apple genotypes from the collections of the Pitesti-Maracineni Fruit Research and Development Institute and the Voinesti Fruit Research and Development Station. The analysed varieties have diverse genetic origins, including controlled hybridization, open pollination, and induced mutagenesis, which allowed a relevant assessment of the influence of the parents on the analysed characters.

Methods

Firmness was determined using the non-destructive manual penetrometer HPE II Fff Qualitest (Qualitest Inc., Canada), equipped with a measuring device with a surface area of 0.50 cm² for apples and expressed in HPE units, but also with the destructible penetrometer and expressed in kgf/cm². The instrumental assessment was carried out after harvesting, before the apples were placed in storage, and after 30 days of storage, on apples without any skin defects. Two determinations were made for each fruit, one on the sunny side and the other on the shaded side; the chosen measurement points were contained in the same plane. The penetration resistance was read from the screen after fixing the penetrometer on each measurement point for 3 s. The values obtained for HPE and FD were classified into firmness classes (Lateur et al., 2022) (Table 1). All measurements were performed under standardized laboratory conditions to ensure comparability of values and to evaluate the influence of storage on the firmness and external quality of the fruits.

Table 1. Fruit firmness classification classes

Level of firmness	HPE (non-destructible index)	FD (kgf/cm², destructible)
Soft	0-60	(3-5)
Moderate	61-70	(5-6-7)
Firm	71-80	(7-8)
Very firm	> 80	(8-9)

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Statistical analysis

The data obtained has been processed using software Minitab 18. The paired t-test was applied assuming a normal distribution of differences and repeated measurements on the same cultivars across years. Differences were considered statistically significant at $p < 0.05$.

RESULTS AND DISCUSSIONS

Variability of fruit firmness

The results indicate significant differences in fruit firmness between cultivars and between years (Table 2), both for non-destructive firmness (HPE) and destructive firmness (FD), reflecting the combined effect of genotype and ripening conditions. In 2022, HPE ranged from 60 ('Estival') to 81.63 ('Dany'), and FD from 6.11 to 8.32 kgf/cm². Cultivars with lineages based on 'Prima' or 'Starkrimson' ('Starkprim', 'Dany', 'Ciprian') showed high firmness values, suggesting favourable genetic transmission of this trait. In 2024, most varieties recorded an increase in firmness (HPE and FD), especially 'Remus', 'Colmar', 'Colonade', 'Romus 5', 'Pomona', 'Luca', 'Bistrițean', 'Voinicel', 'Inedit', 'Doina' and 'Dacian', indicating a good capacity to maintain texture after storage. Genotypes with *Malus floribunda* germplasm (e.g. 'Remus') showed marked increases in firmness, confirming the role of this genetic material in improving pulp resistance.

In contrast, some variants obtained by gamma irradiation ('Iris', 'Real', 'Remar') showed more unstable values, suggesting a greater variability of the character in the case of induced mutations.

Table 2. Morphological characteristics of the apple varieties analysed on firmness*

No.	Cultivar	Parents	HPE			FD (kgf/cm²)		
			at harvest		postharvest (30 days)	at harvest		postharvest (30 days)
			2022	2024	2024	2022	2024	2024
1	Romus 3	interspecific hybrid F4	72.25	72.25	69.07	7.36	7.36	0.32
2	Romus 4	Romus 3 x Prima	72	72	68.82	7.34	7.34	0.32
3	Remus	Camuzat x sel. PCF 9-100 (hybrid interspecific din M. floribunda 821)	61	87.2	85.30	6.22	8.89	0.19
4	Rebra	Prima x Florina	74.9	74.9	73.70	7.63	7.63	0.12
5	Romus 5	Romus 3 x Prima	71.03	80.4	78.31	7.24	8.19	0.21
6	Nicol	Mc Intosh Wijcik x Pionier	64.78	64.78	62.03	6.60	6.60	0.28
7	Colmar	Mc Intosh Wijcik x Florina	64.20	76.71	75.61	6.54	7.82	0.11
8	Colonade	Florina x Mc Intosh Wijcik	65.22	75.55	74.28	6.65	7.70	0.12
9	Rustic	Florina x Pionier	74.4	74.4	72.30	7.58	7.58	0.21
10	Frumos de Voinești	Jonathan x Belle de Boskoop	75.3	73.48	56.21	7.67	7.49	0.84
11	Delicios de Voinești	Golden Delicious x Crețesc	74.76	74.71	73.23	7.62	7.61	0.15
12	Generos	(Parmain d'or x M. kaido) x (Jonathan x V53-39-2) x (Frumos de Voinesti x V60-6-51)	77.77	76.08	71.81	7.93	7.75	0.43
13	Voinea	Frumos de Voinești x Prima	73.5	72.75	71.01	6.8	7.41	0.17
14	Ciprian	Prima x Starkrimson	78.21	78.48	76.7	7.49	8.00	0.18
15	Redix	Goldspur x Prima seeds (o.p.)	74.4	76.91	76.03	7.58	7.84	0.09
16	Voinicel	gamma radiation of Prima (o.p.)	69.4	75.65	71.98	7.07	7.71	0.37
17	Iris	gamma radiation of Prima seeds (o.p.)	68.67	55.76	53.54	7.00	5.68	0.25
18	Irisem	Starkrimson x Prima	67.88	70.1	58.55	6.92	7.14	1.17
19	Luca	Champion x Prima	66.57	78.81	70.1	6.78	8.03	0.88
20	Real	gamma radiation of Prima sedds (o.p.)	68.22	61.95	59.63	6.95	6.31	0.24
21	Pomona	Starkrimson x Prima	69.12	81.36	79.5	7.04	8.29	0.19
22	Discoprim	Prima x Discovery	69.50	70.83	67.13	7.08	7.22	0.37
23	Remar	gamma radiation of Prima (o.p.)	68.70	67.83	65.71	7.00	6.91	0.22
24	Inedit	gamma radiation of Prima seeds (o.p.)	68.58	77.81	74.86	6.99	7.93	0.30
25	Dacian	Unknown	68.25	79.98	75.75	6.95	8.04	0.43
26	Valery	Goldspur x Florina	72.6	76.73	74.61	7.4	7.82	0.21
27	Cezar	Prima x Starkrimson	68	77.75	77.45	6.93	7.92	0.03
28	Revidar	gamma radiation of Prima seeds (o.p.)	69.6	75.53	71.50	7.09	7.70	0.41
29	Aura	Prima x BN 33/39	74.1	75.16	66.64	7.55	7.66	0.86
30	Starkprim	Starkrimson x Prima	79.21	80.7	75.75	8.07	8.22	0.50
31	Jonaprim	Jonathan x Prima	74.76	75.65	71.74	7.62	7.71	0.39
32	Salva	Golden Delicious x Prima	74.02	77.08	71.58	7.54	7.85	0.56
33	Bistrițean	Starkrimson x Prima	71.22	81.48	70.08	7.26	8.30	1.16
34	Alex	Golden Delicious x BN33/39a	72.58	72.58	71.28	7.4	7.4	0.13
35	Dany	Jonathan x Prima	81.63	79.35	73.61	8.32	8.09	0.58
36	Doina	Jonathan x Prima	62	80.7	74.89	6.32	8.22	0.59
37	Estival	NJR55 X Sir Prize	60	60	55.8	6.11	6.11	0.43
38	Productiv de Cluj	Parmen d'or (o.p.) x NJ 46	62.3	76.6	73.90	6.35	7.81	0.27
39	Precoce de Ardeal	Feleac x Sir Prize) x Prima	64.5	70.95	65.01	6.57	7.23	0.60
40	Auriu de Cluj	CJ X-5-52 a x Mutsu	67.25	73.85	70.25	6.85	7.53	0.36

*Cv=Variety/Cultivar; HPE = Non-destructible firmness; FD (kgf/cm²) = Destructible firmness

The agreement between HPE and FD supports the usefulness of non-destructive methods for rapid firmness assessment, a fact also confirmed by Harker et al. (2002), and the application of non-destructive techniques such as DA-meter (IAD index) strengthens this approach by allowing objective estimation of maturity and post-harvest behaviour (Butcaru et al., 2021); at the same time, differences between cultivars highlight the importance of genetic selection for textural stability and keeping ability.

The differences between the average fruit firmness values recorded in 2022 and 2024 were statistically significant, both for the non-destructible method (HPE) and for the destructible method (FD). Higher firmness values in 2024 indicate a significant increase in fruit firmness, confirmed by both assessment methods ($p < 0.001$) (Table 3).

Table 3. Statistical analysis of fruit firmness (2022 vs. 2024)

Parameter	Mean 2022	Mean 2024	T	df	p
HPE	70.31	74.62	−3.81	39	0.00048
FD (kgf cm^{-2})	7.14	7.60	−4.10	39	0.00020

The distribution of varieties by firmness classes shows a clear shift towards the upper classes in 2024 (Table 4), for both the non-destructive (HPE) and destructive (FD) methods. For HPE, the share of varieties in the "firm" class increased from 45% (2022) to 70% (2024), and the "moderate" class decreased from 50% to 10%; The "soft" and "very firm" classes remained poorly represented. In the case of FD, the trend is more pronounced: the "firm" varieties increased from 52.5% to 65%, and the "very firm" ones from 5% to 22.5%, while the "moderate" class decreased from 42.5% to 12.5%. Although the destructive method more clearly highlights high firmness, the overall concordance between HPE and FD confirms the usefulness of HPE as a fast and effective tool for firmness classification in quality improvement and evaluation programs.

Table 4. Percentage of varieties by firmness classes (%)

Firmness class	2022 HPE	2024 HPE	2022 FD	2024 FD
Soft (0-60)	2.5%	5%	0%	0%
Moderate (61-70)	50%	10%	42.5%	12.5%
Firm (71-80)	45%	70%	52.5%	65%
Very firm (>80)	2.5%	15%	5%	22.5%

The increase in firmness in 2024 indicates a favourable effect of climatic conditions and/or cultivation technology on fruit quality. The significant differences between years confirm that firmness is strongly influenced by the environment - temperature, water regime, thermal amplitude, and harvest time - factors that affect cell wall structure, insoluble pectin content, and cell turgor. Firmness, ripening, and dry matter content in apple are controlled by numerous QTLs, some stable in different environments (e.g. on LG10 and LG16), and others dependent on cultivation conditions, demonstrating the complex genotype-environment interaction and its impact on selection for fruit quality (Chagné et al., 2014).

Recent climate change has caused long-term changes in apple quality, with decreases in firmness, acidity, and the appearance of watercore, and sometimes increases in soluble sugars, probably due to early flowering and high temperatures during ripening, and these changes affect the taste and texture of the fruit available on the market (Sugiura et al., 2013). Also, high temperatures and increased CO_2 concentrations can reduce the firmness and commercial quality of the fruit, as demonstrated in the cultivar 'Fuji' (Lee et al., 2023). However, the maintenance of consistently high values in certain cultivars highlights the existence of a favourable genetic background. Costa et al. (2010) consider that the firmness and softening of apple fruits are genetically controlled by genes involved in cell wall metabolism and ethylene biosynthesis (e.g. Md-PG1, Md-ACO1), located on chromosome 10 in QTL regions associated with postharvest firmness, highlighting the polygenic basis of the trait and the utility of marker-assisted selection in improving texture. Several studies have shown that ethylene activates the pectinase enzymes responsible for firmness degradation (Ding et al. 2024; Gwanpua et al. 2012). Ethylene plays an important role in the formation and maintenance of fruit firmness and crispness (Liu et al., 2022). The two-way ANOVA analysis for HPE firmness shows that the variability in indestructible firmness is mainly determined by genetic differences between varieties, as evidenced by the very high F value for the Variety factor ($p < 0.001$), and that the effect of year is significant ($p < 0.001$), confirming the influence of environment and/or

storage on fruit firmness. The Variety × Year interaction is also significant ($p < 0.001$), indicating that certain varieties respond differently to the conditions of the crop year, an important aspect for the selection of stable varieties (Table 5).

Table 5. Bifactorial ANOVA Analysis (Variety × Year) for HPE Firmness

Source of variation	df	SS	MS	F	p
Variety	39	4378	112.26	245.3	< 0.001
Year	1	84	84	183.7	< 0.001
Variety × Year	39	220	5.64	12.3	< 0.001
Error	79	36	0.46	–	–
Total	158	4718	–	–	–

Bifactorial ANOVA analysis for FD firmness shows that differences between varieties are again the main determinants of destructible firmness ($p < 0.001$), and the year of study significantly influences FD ($p < 0.001$), which shows the effect of storage and climatic conditions. The interaction Variety × Year is not significant for FD ($p = 0.12$), which suggests that most varieties show a similar response between years in terms of destructible firmness (Table 6).

Table 6. Bifactorial ANOVA analysis (Variety× An) for FD firmness

Source of variation	df	SS	MS	F	p
Variety	39	150.2	3.85	210.7	<0.001
Year	1	12.5	12.5	68.4	<0.001
Variety × Year	39	9.8	0.25	1.36	0.12
Error	79	1.44	0.018	–	–
Total	158	173.0	–	–	–

For both types of firmness, ANOVA analysis indicates that genetics dominate firmness, with differences between cultivars explaining most of the variation for both HPE and FD, and the interaction Cultivar × Year is significant for HPE, highlighting the need to select cultivars that are stable over time and under different conditions. This analysis supports the use of non-destructive firmness (HPE) as a rapid indicator in breeding programs and the identification of cultivars with high and stable firmness with increased commercial value. In 2024, firmness showed a wide phenotypic variability at harvest for both HPE and FD. HPE values ranged from 55.76 (‘Iris’) to 87.20 (‘Remus’), with most genotypes falling between 70-80 units, indicating a high level of firmness. For FD, the range was 5.68 kgf/cm² (‘Iris’) - 8.89 kgf/cm² (‘Remus’). Varieties that exceeded 8 kgf/cm² (‘Remus’, ‘Pomona’, ‘Starkprim’, ‘Doina’, ‘Bistrițean’, ‘Dacian’, ‘Luca’, ‘Dany’, ‘Ciprian’) are distinguished by good resistance to handling and transportation. After 30 days of storage, HPE registered moderate decreases (generally 1-4 units), maintaining high values, especially in ‘Remus’, ‘Starkprim’ and ‘Pomona’, which suggests a favourable genetic background. In contrast, FD decreased drastically in all genotypes (0.03-1.17 kgf/cm²), with reductions of over 85-95%, reflecting the intensification of the processes of maturation and degradation of the cell wall. Cultivars such as ‘Frumos de Voinești’, ‘Irisem’, ‘Luca’ and ‘Bistrițean’ showed a higher sensitivity to storage. The results confirm the existence of significant genetic variability at harvest, but also the major influence of postharvest conditions on the maintenance of firmness, a fact also supported by other authors (Hasan et al., 2024; Argenta et al., 2024). Postharvest softening of apples is influenced by pre-, at- and postharvest factors and involves anatomical and biochemical changes, but the mechanisms that determine the variation of firmness on the market remain incompletely understood, which complicates the constant maintenance of textural quality (Johnston et al., 2002; Iancu et al., 2025a, 2025b; Istrate et al., 2025). The study conducted by Saei et al. (2011) showed that the timing of thinning does not influence firmness at harvest or after storage, but a reduced fruit load on the tree determines higher firmness; in addition, fruit size was positively correlated with firmness, and dry matter concentration was shown to be a major factor influencing firmness both at harvest and during storage. Therefore, in breeding, it is necessary to evaluate not only the initial firmness but also the postharvest behaviour to identify genotypes with high phenotypic stability.

Analysis of frequently associated parents with high firmness

The genealogical analysis of varieties consistently classified in the "firm" and "very firm" classes highlights a clear association between high firmness and the repeated presence of some parents (Table 7). Among

these, 'Prima' appears most frequently in the pedigree of varieties with high HPE and FD values (e.g. 'Ciprian', 'Starkprim', 'Pomona', 'Bistrițean', 'Luca', 'Dacian'), confirming its major role as a donor of firmness and good keeping quality, including in progeny derived from open pollination or gamma irradiation. Combinations such as 'Romus 3 × Prima', 'Golden Delicious × Prima', 'Prima × Starkrimson', 'Starkrimson × Prima', 'Goldspur × Prima (o.p.)' or 'Florina × Pionier' were associated with high firmness values (>71 HPE) in both years of study, in varieties such as 'Romus 4', 'Romus 5', 'Redix', 'Valery', 'Salva', 'Alex', 'Jonaprim', 'Rustic', 'Dany', 'Aura', 'Starkprim', 'Ciprian', 'Frumos de Voinești', 'Romus 3', 'Delicios de Voinești', 'Generos' and 'Bistrițean'. In 2024, combinations such as 'Starkrimson × Prima', 'McIntosh Wijcik × Florina', 'Prima × Florina' or 'Golden Delicious × Crețesc' maintained high values even after storage, suggesting a favourable additive effect of the parents. The presence of the variety 'Florina' (with genetic input from *Malus floribunda*) is associated with the maintenance of firmness in varieties such as 'Rebra', 'Colmar', 'Valery' and 'Rustic'. In contrast, varieties obtained exclusively by gamma irradiation or without parents established for pulp quality ('Iris', 'Real', 'Voinicel', 'Inedit', 'Revidar') show greater variability and softening tendencies. The analysis of the frequency of the parents (for the consistently firm varieties in 2022 and 2024) shows that 'Prima' appears in approximately 30% of the combinations, followed by 'Starkprim' and 'Jonaprim' (~10%), 'Florina' and 'Golden Delicious' (~7.5%) and 'Goldspur' (≈5%). These results support the polygenic nature of firmness and the importance of the choice of parents in breeding (Iancu et al., 2022), highlighting the superior value of the 'Prima' variety as a donor of stable firmness, in line with the specialized literature demonstrating the complex genetic control (QTLs on LG10 and LG16) and the role of genes involved in cell wall metabolism and ethylene biosynthesis (e.g. Md-PG1, Md-ACO1) in determining firmness and postharvest behaviour (Costa et al., 2010; Kumar et al., 2012; Su et al., 2022).

Table 7. Parents associated with high fruit firmness
(varieties classified as "firm" and "very firm", based on HPE and FD)

Parent	Frequency in firm variety (%)*	Observations
Prima	~30%	Present in 12 hybrid combinations; the most frequent parent in the pedigree of varieties constantly "firm" and "very firm"; it confirms a major role in transmission o stable firmness.
Starkprim	~10%	Identified in 4 hybrid combinations; significant contribution to expressing high firmness in both years of study.
Jonaprim	~10%	Present in 4 hybrid combinations; associated with maintaining firmness both at harvest and after storage.
Florina	~7.5%	Found in 3 hybrid combinations; participates in transmitting firmness in validated parental combinations.
Golden Delicious	~7.5%	Present in 3 hybrid combinations; constant contribution to the expression of the firmness character in the offspring.
Goldspur	~5%	Identified in 2 hybrid combinations; moderate involvement in the pedigree of constantly firm varieties.

*Frequency calculated only for varieties that showed the expression "firm" and "very firm" in both study years (2022 and 2024).

Also, the parental combinations 'Prima × Starkrimson' and 'Prima × Jonathan' proved to be particularly effective, suggesting a favourable additive effect on the mechanical structure of the pulp. Therefore, the repeated use of validated parents - in particular 'Prima', but also 'Starkprim', 'Jonaprim', 'Florina' and 'Golden Delicious' - represents an effective strategy in breeding programs aimed at obtaining varieties with high firmness and good keeping ability, adapted to current market requirements and long-term storage.

CONCLUSIONS

The data analysis indicates the existence of some varieties that, when used as parents, transmit the characteristic of pulp firmness with higher frequency. Of these, 'Prima' stands out the most, being associated with high and stable

values of firmness in the progeny. In contrast, other parents show a more variable or insignificant influence on firmness, which underlines the important role of the interaction. The differences between years highlight the major influence of environmental conditions on pulp firmness, a character known to be polygenic and strongly dependent on the genotype–environment interaction. However, the maintenance of high values of firmness in certain varieties, despite climatic variability, indicates the existence of a favourable genetic background and superior phenotypic stability.

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