Morariu PA *et al.* (2025)
Notulae Botanicae Horti Agrobotanici Cluj-Napoca
Volume 53, Issue 1, Article number 14046
DOI:10.15835/nbha53114046
Research Article

The impact of cultivar and production conditions on apple quality

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Abstract

Cultivar and production conditions influence the quality of apple fruits, and morphological, biochemical, and organoleptic attributes of apples can vary significantly even within the same cultivar. Numerous factors determine the commercial appearance of apples, as well as their nutritional and gustatory value. By comparing eight apple cultivars across different cultivation environments, this study highlights significant variations in tree growth, fruit yield, and quality. The findings reveal that super-intensive systems optimize land use and enhance yield efficiency but may impose physiological constraints that affect fruit size and biochemical composition. 'Starkrimson' and 'Golden Delicious' cultivars recorded the highest production in the intensive system, while 'Granny Smith' performed best in the super-intensive orchard. 'Pinova' demonstrated the highest yield efficiency, supporting its suitability for high-density plantations. Biochemical analyses confirmed substantial variability in dry matter, sugar content, and mineral composition, emphasizing the role of ecological and agronomic factors in shaping fruit quality. Sensory evaluations identified 'Pinova' and 'Golden Delicious' as the most appreciated varieties, reaffirming the importance of sweetness, texture, and aroma in consumer preferences. The study underscores the necessity of integrating genetic, environmental, and sensory analyses in apple research to optimize production and breeding strategies. These findings contribute to the advancement of orchard management practices, ensuring sustainable apple cultivation while maintaining high fruit quality for commercial markets.

Keywords: biochemical composition; consumer preferences; cultivation systems; fruit morphology; nutritional value; orchard management; sensory evaluation; yield efficiency

Received: 01 Aug 2024. Received in revised form: 30 Jan 2025. Accepted: 28 Mar 2025. Published online: 28 Mar 2025.
From Volume 49, Issue 1, 2021, Notulae Botanicae Horti Agrobotanici Cluj-Napoca journal uses article numbers in place of the traditional method of continuous pagination through the volume. The journal will continue to appear quarterly, as before, with four annual numbers.

Introduction

Apple (*Malus* × *domestica* Borkh.) is a fruit species of great economic and nutritional importance. The quality and production of apples depend on several factors, among which cultivation technology and regional ecological conditions play a crucial role (Muder *et al*., 2022; Qu and Zhou, 2016). Modern planting systems, efficient resource management, balanced fertilization, and adaptation to environmental conditions are essential for enhancing yields and improving the fruit's pomological traits (Volk *et al*., 2017).

Farmers and researchers continuously seek the best strategies to maximize orchard productivity while ensuring high standards of quality and sustainability. Tree spacing in an orchard significantly affects both yield and fruit quality (Amarante *et al*., 2008; Wagenmakers and Wertheim, 1991). High-density systems, with a high number of trees per hectare, increase productivity, but can lead to intense competition for light and nutrients, impacting fruit size and quality (Ladon *et al*., 2024). In contrast, lower-density systems, support balanced tree development, allowing for efficient photosynthesis and better sugar accumulation *(Milošević et al*., 2022). The choice of planting density should align with production goals, soil and climatic conditions, and the selected training system. Training systems further optimize tree growth and harvesting efficiency *(Uselis et al*., 2020; Wertheim *et al*., 2001a). Vertical axis and slender spindle systems, along with modern approaches like tall spindle, are increasingly favoured for their capacity to provide uniform distribution of light and simplicity of orchard maintenance (Robinson *et al*., 2013). By reducing tree height, these systems improve fruit exposure to sunlight, enhancing coloration and increasing the concentration of bioactive compounds *(Yuri et al*., 2011). Proper branch management and fruit load regulation are also crucial to preventing overloading, which could result in smaller fruit and alternate bearing cycles (Doğan *et al*., 2024).

Equally important in ensuring fruit quality are tree nutrition and irrigation. Proper fertilization balances macronutrients and micronutrients, avoiding excessive applications that could negatively impact growth and fruiting (Kowalczyk *et al*., 2022; Mditshwa *et al*., 2017). An excess of nitrogen, for example, promotes vegetative growth at the expense of fruit firmness and storage longevity. In contrast, organic and organo-mineral fertilizers enhance the sugar and antioxidant content of the fruit, contributing to improved nutritional value (Li *et al*., 2022). The use of manure and compost-based fertilizers has been shown to improve soil structure and provide long-term nutrient availability compared to intensive chemical fertilization (Roussos and Gasparatos, 2009). Irrigation management plays a direct role in fruit quality, as both water stress and excess moisture can have adverse effects. Water stress results in smaller fruit and lower sugar content, while over-irrigation fosters disease development and reduces pulp firmness. Drip irrigation systems have proven highly effective, ensuring uniform water distribution and stabilizing soil moisture levels. When combined with fertigation, these systems enhance nutrient absorption and improve overall fruit quality (Peck *et al*., 2006b).

Ecological conditions further dictate apple production and quality. High summer temperatures can accelerate fruit ripening but may compromise firmness, while cold winter periods are essential for proper flower bud differentiation (Doğan *et al*., 2024). Solar radiation is a key factor in determining fruit coloration, an important trait for commercial appeal. Excessive rainfall, on the other hand, can promote fungal infections and lower the concentration of soluble solids (Roussos and Gasparatos, 2009). In regions with humid climates, disease management and integrated plant protection strategies are necessary to maintain high production levels and fruit quality (Moinina *et al*., 2019).

The choice of agricultural system also influences apple quality, as conventional and organic farming exhibit distinct characteristics (Reganold *et al*., 2001). Conventional methods rely on intensive mineral fertilization and pesticide use to achieve higher yields but may have long-term environmental and soil health consequences (Peck *et al*., 2006b). In contrast, organic farming prioritizes natural resource utilization and ecological balance, often yielding fruit with higher antioxidant and phenolic compound levels beneficial for human health (Mditshwa *et al*., 2017). However, organic production requires strategic planning and efficient pest control to maintain consistent yields. The interplay of cultivar selection, cultivation technology, and environmental conditions thus shapes apple production and quality (Volk *et al*., 2017). Implementing balanced fertilization, optimal cropping systems, and sustainable water management practices is fundamental to achieving high-quality apples while ensuring long-term environmental sustainability (Fotirić Akšić *et al*., 2022; Liu *et al*., 2024).

Over the years, hybridization has predominantly developed new apple varieties through the controlled crossing of the most valuable parental forms (Sestras and Sestras, 2023). Although a wide array of apple varieties exists, the domestication process has resulted in the erosion of genetic diversity, leading to a reduction in the genetic variability of cultivated forms (Migicovsky *et al*., 2021). This narrowing of the genetic base presents a substantial challenge for the sustainability and resilience of cultivated species in the future (Cornille *et al*., 2012). Therefore, the development of new apple varieties that fulfill modern agricultural demands—such as high productivity, reliability in cultivation, and adaptability to biotic and abiotic stress conditions, including those induced by climate change—is essential (Peil *et al*., 2011). Genetic resources from wild *Malus* species can be utilized to prevent the narrowing of the gene pool in apple cultivars (Dan *et al*., 2015b; Sestras *et al*., 2011). However, recovering the phenotype of the valuable recurrent parent requires a significant amount of time and parental forms with exceptional fruit quality that can transmit the desired traits (Janick *et al*., 1996). Modern selection methods employing molecular markers are playing an increasingly important role in reducing the time required to develop new apple varieties (Brown, 2012; Devi *et al*., 2023; Sestras *et al*., 2009). Nevertheless, phenotypic selection is the definitive way of identifying valuable genotypes, prioritizing the overall quality of the fruits and, especially, their taste attributes. Consequently, ensuring programs, reinforces the need for continued innovation in cultivar development (Teh *et al*., 2021a; Teh *et al*., 2021b).

Beyond apple breeding, consumers frequently encounter variability in apple quality, even among apples of the same cultivar. This variation stems from differences in genetic factors, cultivation practices, harvest timing, and storage conditions (Argenta *et al*., 2022; Mureșan *et al*., 2022; Peck *et al*., 2006a). Consumers may notice fluctuations in taste, texture, flavor, and overall satisfaction depending on the producer, point of sale, and moment of consumption. Understanding the key determinants of apple quality is essential for establishing consistent production and distribution standards that enhance consumer experience and market reliability (Corrigan *et al*., 1997; Harker *et al*., 2008). Various models for the organoleptic evaluation of fruit quality have been proposed and tested. Since these analyses rely on taster preferences, they inherently involve a degree of subjectivity that is challenging to eliminate (Bavay *et al*., 2013; Harker *et al*., 2003). In general, sensory testing involves the participation of trained tasters who assess the commercial appeal of fruits as well as intrinsic characteristics such as pulp texture, juiciness, taste, and aroma (Dan *et al*., 2015a; Morariu *et al*., 2025). These evaluations play a crucial role in understanding consumer preferences and market trends, providing valuable insights for the fruit industry (Jaeger *et al*., 2018; Meike *et al*., 2022). Fruit quality evaluations are particularly important in apple breeding, as they contribute to the promotion of new cultivars and the identification of valuable genotypes for hybridization programs (Corollaro *et al*., 2014; Gavrilă *et al*., 2025).

Based on these considerations, this study sought to conduct a comprehensive analysis of morphological traits, chemical composition, and organoleptic properties to determine whether fruit quality is influenced not only by genetic factors (variety) but also by the conditions under which the fruits are produced. By examining these factors, the study intended to provide insights into how cultivation practices and environmental variables impact both the quantitative and qualitative aspects of apple production. The inclusion of organoleptic analysis was particularly emphasized to assess sensory attributes, which are critical for consumer preference and marketability. This holistic approach was designed to elucidate the interaction between genotype and source of origin of apples, providing valuable information on the complex factors that influence fruit quality.

Materials and Methods

Biological material and experimental conditions

The experiment focused on eight apple varieties (sometimes referred to as cultivars or genotypes) cultivated in two orchards located in Boz village, Doștat commune, Alba County, Central Transylvania, Romania. The study aimed to compare the characteristics of apples grown under different cultivation systems and management practices (intensive cultivation system and super-intensive cultivation system). Five apple varieties—'Golden Delicious', 'Jonathan', 'Florina', 'Idared', and 'Starkrimson'—were cultivated in an intensive system. These trees were trained using the improved open vase management form (open center system) and grafted onto MM106 rootstock. The planting distance was 3 × 4 meters, resulting in a density of 833 trees per hectare. This system is designed for long-term orchard management, emphasizing balanced growth and high-quality fruit production. Four varieties—'Fuji', 'Golden Delicious', 'Granny Smith', and 'Pinova'—were studied in a super-intensive orchard. These trees were trained in the slender spindle management form and grafted onto M9 rootstock. The planting distance was 1 × 4 meters, achieving a high density of 2,500 trees per hectare. This system is optimized for maximizing yield per unit area, with a focus on efficient space utilization and early fruit production. The MM106 rootstock is semi-vigorous, while the M9 is of low vigor (Yıldırım *et al*., 2016). Fertilization and phytosanitary treatments in the Boz orchard adhered to the conventional practices of a commercial orchard, whereas those in the Cluj-Napoca (educational orchard) were diminished. Both orchards benefited from the drip irrigation method. The fruits of the varieties harvested from the Boz orchard (Figure A1) were compared with those from two additional sources: 1. The orchard of the University of Agricultural Sciences and Veterinary Medicine in Cluj-Napoca (except for 'Starkrimson', which came from the Horticultural Research Station, located nearby); 2. Fruits purchased from three retail commercial units in Alba Iulia. The two orchards, in Boz and Cluj-Napoca, have similar pedo-climatic conditions (the distance between them being approx. 100 km), specific to the Transylvanian Plateau, with predominance of luvisols with a high degree of leaching, and a temperate boreal continental climate. The annual precipitation in Boz and Cluj-Napoca varies between 500 and 600 mm, and the average annual temperature is between 8 and 9 °C.

Assessment of tree attributes

In the Boz orchard, the primary growth and fruiting characteristics of trees were analyzed in the tenth year after planting in the intensive orchard and the sixth year after planting in the super-intensive orchard. The assessments were conducted in a completely randomized block design, with three replicates consisting of five trees per replicate.

Tree height was measured from ground level to the highest point of the central axis or canopy. Trunk diameter was determined using an electronic caliper, measured 20 cm above ground level along the direction of the tree row. Shoot length was assessed at the end of the shoot growth period in mid-September, with measurements taken from 5–10 randomly selected shoots per tree. Crown diameter was recorded in both the row direction and perpendicular to it at its widest point, and the average of these two measurements was used as the final value per tree.

Self-fertility, or the capacity for self-pollination, was evaluated by isolating five to six inflorescences per tree within parchment paper bags before flower opening. The number of fruits formed after natural physiological drop, occurring around mid-June, was subsequently counted. Natural or open fertility, representing the ability for cross-pollination (while not excluding self-pollination), was determined by counting the flowers at the time of opening on two or three labeled scaffold branches, followed by a count of the fruits developed on the same branches in mid-June. The data were processed as percentage values of self-fertility and natural fertility (both self- and cross-pollination), calculated as the ratio of the number of fruits formed to the number of flowers counted. Fruit production was assessed by individually weighing all fruits harvested from each tree. Yield efficiency (YE) was calculated using the following formula (Fioravanço *et al*., 2016):

$$YE\ (kg/cm^2) = \frac{Fruit\ yield\ (kg/tree)}{TCSA\ (cm^2)} \quad (1)$$

where the trunk cross-sectional area (TCSA) was determined based on the tree diameter (D) measured in cm, respectively, the radius of the circle (R) using the equation for the area (A) of the circle (Sestras, 2019):

$$A = TCSA\ (cm^2) = \pi R^2 = \pi\left(\frac{D^2}{2^2}\right) = 0.785 \times D^2 \quad (2)$$

Assessment of morphological, biochemical and organoleptic attributes of fruits

Morphological assessments of the fruits were conducted on a sample of 30 randomly selected fruits per variety at the stage of optimal consumption maturity. The samples from the Boz and Cluj-Napoca orchards met commercial quality standards comparable to those of fresh fruit available on the consumer market. Fruit height and width were measured using an ABC caliper, while fruit weight was recorded using a CDE electronic balance. Fruit volume was determined through the water displacement method, measuring the volume of water displaced upon immersion. Pulp firmness was assessed using an SSX penetrometer, whereas the total soluble solids (TSS) content was estimated with a UHGTG refractometer, which provided °Brix sugar measurements. The dry matter content and total mineral content of the fruits were determined through standardized laboratory methods. A portable colorimeter NH300 (3NH, Shenzhen, China) based on the CIE L*a*b* color standard was used to measure the color of apple samples.

The organoleptic evaluation of the fruits was performed by a panel of 20 untrained assessors (10 men and 10 women), who received prior training on the sensory descriptors and evaluation protocol. Each taster independently completed standardized evaluation sheets, referred to as "organoleptic tasting bulletins". The tasters assessed the fruits using a hedonic scale ranging from 1 (very poor, or extremely disliked) to 9 (very good, or extremely liked) for the following attributes: fruit size, shape, and color (as indicators of commercial appearance), as well as pulp color, pulp consistency (texture), juiciness, taste, and aroma (Dan et al., 2015a). Sensory analyses were conducted during the initial ten days of October, at which time the fruits exhibited the varietal characteristics at an optimal level.

Statistical analysis

The evaluation of primary tree and fruit attributes was conducted using average values. Following an assessment of data normality, an analysis of variance (ANOVA) was performed to determine significant differences among the measured parameters. When the null hypothesis was rejected, post hoc analysis was carried out using Duncan's test to delineate and highlight differences among the means related to tree attributes, productivity factors, and the morphological and biochemical characteristics of the fruits. The statistical significance threshold was set at $\alpha < 0.05$. To further analyze the self-fertility and natural fertility of the studied varieties within both cultivation systems (intensive and super-intensive), boxplot visualizations were employed. These boxplots illustrated key statistical parameters, including minimum values, lower quartiles, median, upper quartiles, maximum values, and mean values, providing a comprehensive representation of variability within the dataset. Multivariate analyses were conducted following data normalization, employing PAST software (Hammer *et al*., 2001). The same software was used for principal component analysis (PCA) and hierarchical clustering analyses, the latter applying the single linkage approach and the Gower similarity index to assess relationships among the studied variables.

Results

Tree characteristics according to the cultivation system

The data presented in Table 1 highlight evident differences between trees cultivated in the intensive and super-intensive systems. The height of trees in the intensive system varied between 3.5 and 4.0 meters, whereas in the super-intensive system, tree height was considerably lower, ranging from 2.3 to 2.5 meters. This difference is attributed not only to the cultivation system but also to the younger age of the super-intensive orchard, which is four years younger than the intensive one. For the primary indicator of tree growth, trunk thickness, the intensive system recorded higher trunk diameters, ranging from 12.7 to 18.9 cm, while in the super-intensive system, the trunks were thinner, with diameters between 8.4 and 9.8 cm.

Table 1. Main tree characteristics of five apple varieties in an intensive orchard and four apple varieties in a super-intensive orchard (Boz village, Doștat commune, Alba County, Romania)

Cultivar	Tree height (m)	Trunk height (m)	Trunk diameter (cm)	Shoots length (cm)	Crown diameter (m)
Intensive orchard					
'Golden Delicious'	3.5±0.2 b	57.2±2.9 c	13.3±0.7 b	37.8±2.3 a	2.8±0.2 a
'Jonathan'	3.6±0.2 b	58.8±2.8 b	12.9±0.6 b	38.9±3.1 a	2.7±0.3 b
'Florina'	4.0 ±0.3 a	60.0±3.0 a	18.9±0.9 a	39.0±4.0 a	2.8±0.2 a
'Idared'	3.5±0.2 b	56.8±2.7 c	12.7±0.8 b	31.9±2.9 b	2.7±0.4 b
'Starkrimson'	3.5±0.2 b	57.0±2.6 c	13.0±0.8 b	32.1±2.7 b	2.7±0.3 b
Super-intensive orchard					
'Fuji'	2.4±0.1 b	57.8±2.7 bc	9.2±0.5 b	79.8±5.1 a	0.8±0.1 b
'Golden Delicious'	2.3±0.1 c	57.2±2.8 c	8.4±0.4 c	65.1±4.1 b	0.8±0.2 b
'Granny Smith'	2.5±0.2 a	58.4±2.9 ab	9.8±0.9 a	81.5±4.9 a	0.9±0.3 a
'Pinova'	2.3±0.1 c	59.0±3.1 a	8.7±0.7 c	62.9±3.4 b	0.9±0.2 a

* According to Duncan's test ($\alpha < 0.05$), no significant difference exists between any two means in a column followed by the same letter for each trait (the comparison is separate, only between the varieties in each orchard).

Significant differences were observed among the five varieties in the intensive system, as well as among the four varieties in the super-intensive system, regarding key tree growth parameters. In the intensive orchard, 'Florina' exhibited superior vigor, particularly in terms of significantly greater tree height and trunk diameter compared to the other varieties. Similarly, in the super-intensive plantation, 'Granny Smith' stood out as the most vigorous variety for the same two traits. Shoot length was greater in the super-intensive system, with 'Fuji' recording the highest value at 79.8 cm, compared to 37.8 cm for 'Golden Delicious' in the intensive system. Trees in the intensive system also had a larger crown diameter, ranging from 2.7 to 2.8 meters, whereas in the super-intensive system, the crown diameter was significantly smaller, between 0.8 and 0.9 meters. Although these differences might seem minor, statistical analyses revealed significant variations among the varieties within each plantation.

Yield characteristics depending on variety and cultivation system

The factors influencing effective pollination and fertilization of flowers, as well as fruit development in apple trees, such as self-fertility and natural fertility, exhibited varying values based on the cultivar and cultivation conditions (Figure 1). Percentage values of self-fertility (self-pollination) in intensive orchard ranged from limited to extremes of ample, ranging from 16.8% ('Starkrimson') to 67.4% ('Golden Delicious'). 'Jonathan' and 'Florina' had close average values (between 38-42%), and 'Idared' slightly higher (49%). In the super-intensive orchard, the highest self-fertility values were recorded for 'Pinova' and 'Golden Delicious' (60.5% and 57.2% respectively). The weakest self-pollination capacity was presented by 'Fuji' (38.2%).

Natural fertility, assessed as open or cross-pollination, in intensive orchard ranged from limited to extremes of ample, ranging from 37.5% ('Starkrimson') to 80.1% ('Golden Delicious'). 'Jonathan', 'Florina' and 'Idared' had similar average values (55-58%). In the super-intensive orchard, the highest natural fertility values was recorded for 'Golden Delicious' (76.3%), and the lowest for 'Fuji' (61.0%).

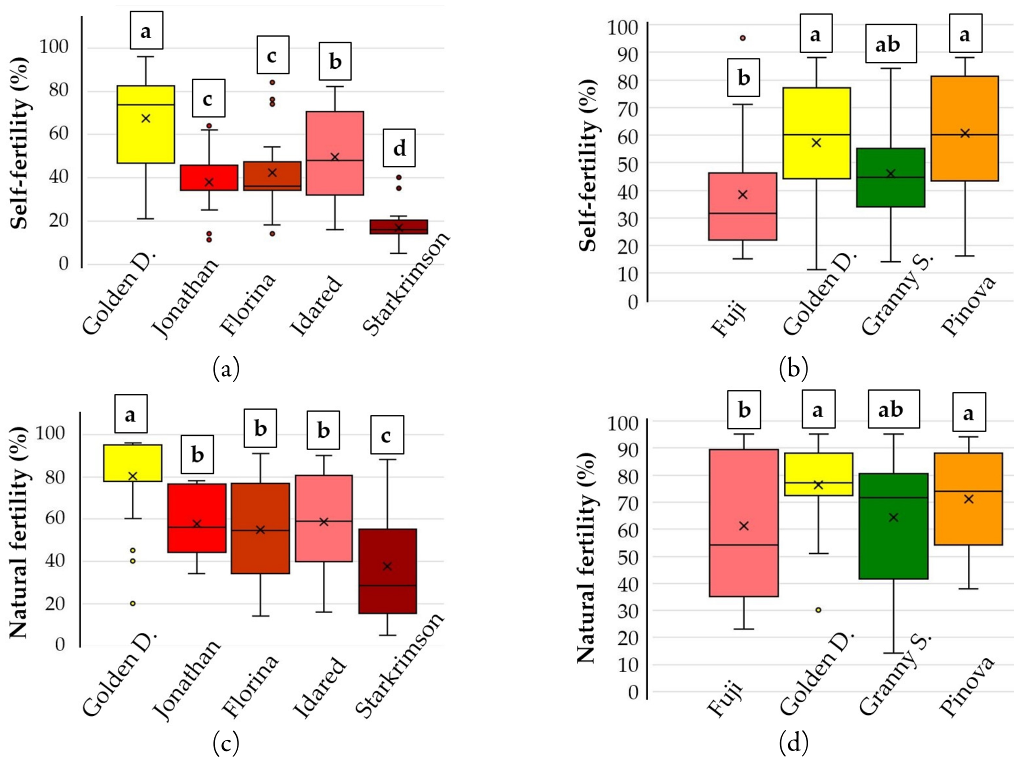


Figure 1. Percentage values of self-fertility (self-pollination) and natural fertility (open or cross-pollination): (**a**) Five cultivars in intensive cultivation system; (**b**) Four cultivars in super-intensive system; (**c**) Five cultivars in intensive cultivation system; (**d**) Four cultivars in super-intensive system. Inside the box, the small '×' represents the mean value of the feature

According to Duncan's test (α < 0.05), no significant difference exists between any two means in a column followed by the same letter for each trait

Fruit production and yield efficiency showed significant differences between varieties in both intensive and super-intensive orchards (Figure 2). In the intensive orchard, the highest production was recorded for 'Starkrimson' (49.5 kg/tree), followed by 'Golden Delicious' (45.8 kg/tree). The other three varieties, 'Jonathan', 'Florina' and 'Idared', had significantly lower productions, with limits ranging between 33.2 kg/tree and 37.4 kg/tree. In the super-intensive orchard, the highest fruit yield was obtained for 'Granny Smith' (32.0 kg/tree), followed by 'Pinova' (28. kg/tree). In contrast, 'Golden Delicious' recorded a significantly lower production (21.1 kg/tree).

In the intensive orchard, the highest yield efficiency was recorded for 'Starkrimson' (0.376 kg/cm^2), followed by 'Golden Delicious', but with a significant deviation. At the opposite pole was 'Florina', with the lowest yield efficiency value (0.134 kg/cm^2). In the super-intensive orchard, the highest yield efficiency was shown by the 'Pinova' variety (0.481 kg/cm^2), followed by 'Granny Smith'. On the contrary, the lowest value of this production indicator was recorded for 'Fuji' (0.364 kg/cm^2).

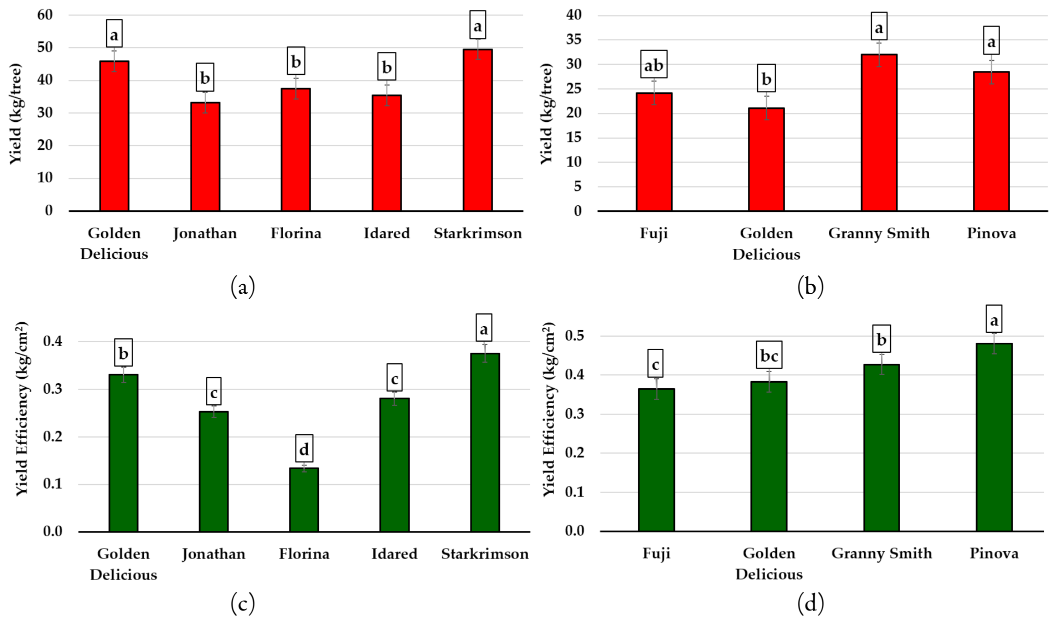


Figure 2. Fruit production and yield efficiency of the studied apple cultivars: (**a**) Yield of five cultivars in intensive cultivation system; (**b**) Yield of four cultivars in super-intensive system; (**c**) Yield efficiency of five cultivars in intensive cultivation system; (**d**) Yield efficiency of four cultivars in super-intensive system According to Duncan's test ($\alpha < 0.05$), no significant difference exists between any two means in a column followed by the same letter for each trait.

Morphological characteristics of fruits according to variety and three sources of origin

The analysis of the main morphological characteristics of the fruits in Table 2 highlights the wide variation in the height, diameter, volume, and weight of the fruits within the eight cultivars and three sources of fruit origin. The only fruit parameter that did not exhibit statistically significant differences based on the place of origin was fruit height in the 'Starkrimson' variety. Among all evaluated cultivars, fruit height ranged from 50.9 mm in 'Fuji' from the Cluj-Napoca orchard to 79.5 mm in 'Golden Delicious' from the Boz orchard. Fruit diameter varied significantly, with the smallest recorded value of 64.4 mm in 'Starkrimson' from the retail establishment source and the largest of 92.5 mm in 'Idared' from the Boz orchard. Fruit volume exhibited a broad range, spanning from 130 ml in 'Fuji' from the Cluj-Napoca orchard to 340 ml in 'Idared' from the Boz orchard. Similarly, fruit weight showed substantial variability, with the lowest value recorded at 113.6 g in 'Idared' from the Cluj-Napoca orchard and the highest at 280.1 g in 'Idared' from the Boz orchard.

Table 2. The main morphological characteristics of the fruits of eight apple varieties from three sources: Boz orchard, Cluj-Napoca orchard, and purchased from the retail establishment

No*	Cultivar	Orchard/ Source	Fruit height (mm)	Fruit width (mm)	Fruit volume (ml)	Fruit weight (g)
1	'Golden Delicious'	Boz	79.5±4.8 k	83.0±5.9 i	293.3±17.6 i	236.5±14.9 ij
2		Cluj-Napoca	65.3±4.1 e-g	71.6±5.1 c-e	190.0±14.8 c-e	157.6±11.7 c-e
3		Retail	75.2±5.1 i-k	77.1±4.9 f-h	233.3±16.8 f-h	193.0±14.7 f-h
4	'Jonathan'	Boz	60.1±5.9 b-e	71.0±5.8 b-e	163.3±9.6 a-c	133.4±9.7 a-c
5		Cluj-Napoca	57.5±3.5 b-d	67.6±4.1 a-d	156.7±8.7 a-c	119.5±8.1 ab
6		Retail	60.1±5.7 b-e	68.9±5.3 a-e	166.7±9.2 a-c	126.8±7.8 a-c
7	'Florina'	Boz	69.8±4.7 f-i	81.0±6.1 h-i	266.7±15.4 hi	216.1±13.4 g-i
8		Cluj-Napoca	60.1±5.2 b-e	70.2±5.8 a-e	176.7±10.7 b-d	142.9±8.7 a-d
9		Retail	60.0±5.1 b-e	69.9±5.4 a-e	180.0±11.4 b-d	149.3±8.3 b-d

10	'Idared'	Boz	77.6±4.7 j-k	92.5±4.7 j	340.0±20.7 j	280.1±16.8 k
11		Cluj-Napoca	54.5±3.4 a-b	66.0±6.2 a-c	153.3±7.8 a-c	113.6±8.2 a
12		Retail	66.7±5.7 e-h	80.3±7.1 h-i	273.3±16.7 hi	202.9±12.7 f-h
13	'Starkrimson'	Boz	61.4±4.7 c-e	65.6±6.8 ab	146.7±11.7 a-c	126.7±7.8 a-c
14		Cluj-Napoca	62.1±5.2 c-e	65.4±4.8 ab	136.7±10.4 ab	124.8±7.1 a-c
15		Retail	61.9±5.3 c-e	64.4±5.1 a	146.7±14.3 a-c	114.5±6.9 ab
16	'Fuji'	Boz	62.5±4.7 c-e	71.8±6.7 d-f	183.3±11.8 c-e	159.8±14.7 c-e
17		Cluj-Napoca	50.9±4.7 a	66.0±4.3 a-c	130.0±9.8 a	114.5±7.1 ab
18		Retail	74.5±6.1 i-k	82.7±8.0 h-i	293.3±17.8 i	251.1±15.7 jk
19	'Granny Smith'	Boz	72.3±5.9 h-j	80.7±10.8 h-i	256.7±16.7 g-i	221.1±14.7 h-j
20		Cluj-Napoca	57.0±4.8 b-c	70.2±9.7 a-e	163.3± 8.7 a-c	132.6±10.6 a-c
21		Retail	60.5±6.1 b-e	67.3±5.7 a-d	163.3±8.1 a-c	126.4±9.8 a-c
22	'Pinova'	Boz	71.4±4.5 g-j	78.0±4.6 g-i	243.3±15.7 f-h	199.5±11.7 f-h
23		Cluj-Napoca	63.8±5.6 d-f	79.0±8.7 g-i	213.3±12.7 d-f	185.3±11.3 e-g
24		Retail	69.9±4.7 f-i	74.6±5.1 e-g	223.3±12.9 e-g	170.6±9.8 d-f

* The studied fruits at 'Golden Delicious' were sourced from the intensive orchard. According to Duncan's test (α < 0.05), no significant difference exists between any two means in a column followed by the same letter for each trait.

'Idared' exhibited the highest values in the Boz orchard, with a fruit height of 77.6 mm, a width of 92.5 mm, a volume of 340 ml, and a weight of 280.1 g. In contrast, the same cultivar presented significantly smaller dimensions in the Cluj-Napoca orchard, with a height of 54.5 mm and a width of 66.0 mm. For the 'Golden Delicious' cultivar, apples from the Boz orchard had a mean weight of 236.5 g, which was higher than those from the Cluj-Napoca orchard (157.6 g) and those sourced from the retail (193.0 g). Regarding the 'Jonathan' cultivar, apples from Boz weighed 133.4 g, whereas those from Cluj-Napoca were significantly lighter, at only 119.5 g.

A unilateral analysis of the effect of variety on fruit morphological characteristics across the three sources of origin revealed statistically significant differences among the tested cultivars (Table 3). The mean fruit height ranged from 59.2 mm in 'Jonathan' to 73.4 mm in 'Golden Delicious', whereas fruit diameter varied between 65.1 mm in 'Starkrimson' and 79.6 mm in 'Idared'. Fruit volume exhibited substantial variation among cultivars, with values ranging from 162.2 ml in 'Jonathan' to 255.6 ml in 'Idared'. Similarly, fruit weight showed considerable variability, with a minimum of 122.0 g recorded in 'Starkrimson' and a maximum of 195.7 g in 'Golden Delicious'.

Table 3. The impact of cultivar on the main morphological characteristics of the fruits, regardless of their source (Boz orchard, Cluj-Napoca orchard, and retail establishment)

No*	Cultivar	Fruit height (mm)	Fruit width (mm)	Fruit volume (ml)	Fruit weight (g)
1	'Golden Delicious'	73.4±4.6 D	77.2±5.1 D	238.9±14.3 CD	195.7±11.4 DE
2	'Jonathan'	59.2±3.9 A	69.2±5.9 B	162.2±7.9 A	126.6±8.4 A
3	'Florina'	63.3±4.2 AB	73.7±6.7 C	207.8±14.2 BC	169.5±9.7 BC
4	'Idared'	66.3±4.7 BC	79.6±6.1 D	255.6±13.9 D	198.9±9.1 E
5	'Starkrimson'	61.8±3.8 AB	65.1±5.7 A	143.3±6.7 A	122.0±5.8 A
6	'Fuji'	62.6±3.5 AB	73.5±6.8 C	202.2±11.5 B	175.1±7.8 B-D
7	'Granny Smith'	63.3±3.6 AB	72.8±6.3 C	194.4±10.3 B	160.0±8.1 B
8	'Pinova'	68.3±4.1 C	77.2±5.5 D	226.7±12.6 B-D	185.1±10.4 C-E

* 'Golden Delicious' fruits from the Boz orchard were obtained from the intensive orchard. According to Duncan's test ($\alpha < 0.05$), no significant difference exists between any two means in a column followed by the same letter for each trait.

The unilateral influence of the fruit's source of origin on their physical and morphological characteristics, irrespective of variety, revealed statistically significant differences among sources for all analyzed parameters (Table 4). Overall, apples sourced from the Boz orchard exhibited greater dimensions and higher weights compared to those from Cluj-Napoca and commercial sources. All evaluated traits recorded significantly higher values in fruits from the Boz orchard. Conversely, apples from the Cluj-Napoca orchard displayed the lowest recorded values across all measured parameters, indicating substantial deviations from the other two sources.

Table 4. The impact of source of origin of apples on the main morphological characteristics of the fruits, regardless of the cultivars (eight apple cultivars)

No*	Orchard	Fruit height (mm)	Fruit width (mm)	Fruit volume (ml)	Fruit weight (g)
1	Boz orchard	69.3±4.2 C	77.9±6.4 C	236.7±14.1 C	196.7±10.4 C
2	Cluj-Napoca orchard	58.9±3.1 A	69.5±7.1 A	165.0±9.5 A	136.4±6.8 A
3	Retail establishment	66.1±5.8 B	73.2±5.9 B	210.0±11.2 B	166.8±8.7 B

* 'Golden Delicious' fruits from the Boz orchard were obtained from the intensive orchard. According to Duncan's test ($\alpha < 0.05$), no significant difference exists between any two means in a column followed by the same letter for each trait.

Firmness and biochemical characteristics of fruits according to variety and three sources of origin

Fruit firmness and various chemical components that influence the taste and nutritional quality of apples demonstrated significant variability among the studied varieties, influenced by the interaction between genotype and source of origin (Table 5), which highlights the role of ecological and cultivation conditions in shaping these attributes.

Fruit firmness displayed a broad range, with values extending from 17.2 N in 'Jonathan' sourced from the retail to 32.8 N in 'Starkrimson' grown in the Boz orchard. Total soluble solids (TSS), measured in °Brix, varied from 8.3 in 'Golden Delicious' from the Cluj-Napoca orchard to 16.1 in 'Starkrimson' obtained from the retail. Dry matter content also showed considerable variation, ranging from 10.7% in 'Golden Delicious' sourced from the retail to 22.1% in 'Starkrimson' from the Cluj-Napoca orchard. Similarly, the total mineral content spanned from a minimum of 0.64% in 'Jonathan' sourced from the retail to a maximum of 1.54% in 'Florina' obtained from the retail.

Table 5. The main physical and biochemical characteristics of the fruits of eight apple varieties from three sources: Boz orchard, Cluj-Napoca orchard, and purchased from the retail establishment

No*	Cultivar	Orchard/ Source	Firmness (N)	TSS (°Brix)	Dry mass (%)	Mineral substances (%)
1	'Golden Delicious'	Boz	17.7±1.1 ab	9.2±0.6 ab	16.0±1.2 gh	1.29±0.07 e-g
2		Cluj-Napoca	20.2±2.9 b-d	8.3±0.7 a	15.3±1.1 fg	1.41±0.09 g-i
3		Retail	22.6±3.4 de	9.0±0.7 ab	10.7±1.0 a	1.51±0.10 i
4	'Jonathan'	Boz	22.7±3.5 de	10.9±0.7 ab	15.4±1.3 fg	1.18±0.07 c-f
5		Cluj-Napoca	20.8±2.8 cd	11.5±0.8 a-d	15.1±1.2 e-g	0.76±0.06 a
6		Retail	17.2±1.9 a	11.2±0.9 a-d	13.4±0.9 b	0.64±0.04 a
7	'Florina'	Boz	17.6±1.7 ab	14.3±1.2 de	15.9±1.5 gh	0.69±0.06 a
8		Cluj-Napoca	25.9±5.1 f-i	11.2±1.1 a-d	15.2±1.6 e-g	0.74±0.04 a
9		Retail	24.7±4.7 e-g	11.0±0.7 a-c	13.4±0.8 b	1.54±0.10 i
10	'Idared'	Boz	21.3±3.9 d	9.9±0.8 ab	14.9±0.9 d-g	1.19±0.09 d-f
11		Cluj-Napoca	18.5±2.1 a-c	11.5±1.7 a-d	14.5±0.7 c-f	1.05±0.08 b-d
12		Retail	17.2±1.3 a	9.0±1.1 ab	14.5±0.9 c-f	1.33±0.12 f-h
13	'Starkrimson'	Boz	32.8±4.1 l	14.2±1.5 c-e	20.4±1.8 j	1.48±0.14 hi
14		Cluj-Napoca	25.5±3.6 f-i	11.3±1.7 a-d	22.1±1.3 k	1.32±0.12 e-h
15		Retail	24.3±2.7 ef	16.1±1.9 e	21.1±1.5 j	1.29±0.08 e-g
16	'Fuji'	Boz	32.2±4.3 l	10.7±1.8 ab	16.7±1.1 hi	1.01±0.09 bc
17		Cluj-Napoca	27.2±4.8 g-i	10.1±1.2 ab	13.9±0.8 b-d	1.28±0.12 e-g
18		Retail	24.9±3.9 e-h	12.2±1.9 b-d	14.3±0.9 b-f	1.14±0.11 b-e
19	'Granny Smith'	Boz	29.3±3.5 jk	11.0±0.9 a-c	13.6±1.1 bc	1.00±0.08 b
20		Cluj-Napoca	30.3±4.1 kl	8.8±0.7 a	17.1±1.2 i	1.07±0.13 b-d
21		Retail	27.5±3.1 h-j	11.1±1.6 a-d	13.2±1.0 b	1.25±0.14 e-g
22	'Pinova'	Boz	25.8±2.4 f-i	9.1±0.7 ab	15.4±1.2 fg	1.30±0.11 e-g
23		Cluj-Napoca	18.1±2.1 ab	8.7±0.9 a	15.9±1.3 gh	1.15±0.12 b-e
24		Retail	27.7±5.3 ij	10.5±0.7 ab	14.7±1.2 d-f	1.33±0.22 f-h

* The studied fruits at 'Golden Delicious' were sourced from the intensive orchard. According to Duncan's test ($\alpha < 0.05$), no significant difference exists between any two means in a column followed by the same letter for each trait.

The impact of genotype on fruit firmness and the chemical composition analyzed across all provenances demonstrated significant variability among the cultivars (Table 6). When assessing pulp firmness unilaterally for each variety, irrespective of the fruit's origin, the genotypes were categorized into three distinct groups, ranging between 19.0 N and 29.0 N. Varieties such as 'Granny Smith', 'Fuji', and 'Starkrimson' exhibited superior firmness, while 'Idared', 'Golden Delicious', and 'Jonathan' were grouped among those with the lowest firmness. The Brix sugar content varied from 8.8 to 13.9, with 'Starkrimson' displaying the highest values, followed by a group comprising 'Jonathan', 'Florina', 'Fuji', and 'Granny Smith'. Conversely, 'Golden Delicious', 'Pinova', and 'Idared' formed the group with the lowest Brix sugar content. In terms of dry matter content, the genotypes ranged between two extremes, with 'Golden Delicious' showing the lowest value (14.0%) and 'Starkrimson' the highest (21.2%), while the remaining varieties exhibited intermediate levels. Notably, 'Golden Delicious' stood out for its total mineral content, recording 1.40%, whereas 'Jonathan' had the lowest value at 0.86%. 'Starkrimson' and 'Pinova' also ranked among the varieties with the highest mineral content, alongside 'Golden Delicious'.

Table 6. The impact of cultivar on some physical and biochemical characteristics of the fruits, regardless of their source (Boz orchard, Cluj-Napoca orchard, and retail establishment)

No*	Cultivar	Firmness (N)	TSS (°Brix)	Dry mass (%)	Mineral substances (%)
1	'Golden Delicious'	20.2±1.2 A	8.8±0.8 A	14.0±0.9 A	1.40±0.08 E
2	'Jonathan'	20.2±1.1 A	11.2±0.6 BC	14.6±1.4 B	0.86±0.06 A
3	'Florina'	22.7±1.2 B	12.1±0.7 C	15.1±1.1 BC	0.99±0.07 AB
4	'Idared'	19.0±0.9 A	10.1±0.9 AB	14.7±0.9 B	1.19±0.17 CD
5	'Starkrimson'	27.5±1.8 C	13.9±1.1 D	21.2±1.6 D	1.36±0.22 DE
6	'Fuji'	28.1±2.1 C	11.0±1.4 BC	15.0±1.7 BC	1.14±0.09 BC
7	'Granny Smith'	29.0±2.5 C	10.3±0.8 A-C	14.6±1.1 B	1.10±0.07 BC
8	'Pinova'	23.9±2.4 B	9.4±1.1 AB	15.3±1.3 C	1.26±0.11 C-E

* 'Golden Delicious' fruits from the Boz orchard were obtained from the intensive orchard. According to Duncan's test ($\alpha < 0.05$), no significant difference exists between any two means in a column followed by the same letter for each trait.

Fruit firmness, Brix sugar content, dry matter, and mineral content exhibited significant variations depending on their origins, irrespective of the influence of the cultivar (Table 7). Specifically, the highest fruit firmness was observed in samples originating from the Boz orchard, while the highest Brix sugar content was recorded in fruits obtained from retail establishments, followed by those from the Boz orchard. The dry matter content was most elevated in fruits from the Cluj-Napoca orchard, with those from the Boz orchard ranking second. Additionally, the highest concentration of mineral substances was detected in fruits sourced from retail establishments.

Table 7. The impact of source of origin of apples on the main physical and biochemical characteristics of the fruits, regardless of the cultivars (eight apple cultivars)

No*	Orchard	Firmness (N)	TSS (°Brix)	Dry mass (%)	Mineral substances (%)
1	Boz orchard	24.9±1.4 B	11.2±0.9 AB	16.0±1.2 B	1.14±0.19 A
2	Cluj-Napoca orchard	23.3±1.2 A	10.2±1.4 A	16.1±1.1 B	1.10±0.07 A
3	Retail establishment	23.3±1.8 A	11.3±1.1 B	14.5±1.7 A	1.25±0.11 B

* 'Golden Delicious' fruits from the Boz orchard were obtained from the intensive orchard. According to Duncan's test ($\alpha < 0.05$), no significant difference exists between any two means in a column followed by the same letter for each trait.

Color of fruits according to variety and sources of origin

The analysis of apple color using the CIE L*a*b* standard, as presented in Table 8, reveals significant variations in both pulp and skin color across the eight studied varieties and their three sources of origin. These differences are primarily influenced by genotype and growing conditions, highlighting the role of ecological and cultivation factors in shaping fruit appearance.

Higher L* values, which indicate brighter and lighter pulp, are consistently observed in 'Golden Delicious' (L* ≈ 75.0-77.4), reflecting its characteristic light color. In contrast, 'Fuji' sourced from the retail exhibits the lowest L* value (69.3), suggesting a darker pulp. The red/green component (a*) further differentiates the varieties, with positive values denoting red hues and negative values indicating green tones. 'Granny Smith', with negative a* values (down to -0.6 from retail), displays a distinct greenish pulp, while 'Pinova' (a* = 7.1) and 'Starkrimson' (a* = 5.0-6.4) exhibit pronounced red hues. The yellow/blue component (b*), which corresponds to yellow tones, is highest in 'Starkrimson' (up to 34.3), indicating a vibrant yellow pulp, while 'Idared' and 'Jonathan' show moderate b* values (23-30), reflecting less intense coloration.

Skin color also varied markedly among the varieties. 'Golden Delicious' displays a yellowish skin (b* ≈ 22.4-41.4), while 'Florina' and 'Idared' exhibit stronger red tones (a* ≈ 19-32). 'Granny Smith' is unique, with negative a* values for skin (-4.0), confirming its green skin, which aligns with its visual identity. These variations underscore the interplay between genotype and origin. For instance, 'Starkrimson' from the Boz orchard shows a deep red skin (a* = 22.0) and bright yellow pulp (b* = 34.3), while 'Granny Smith' from the retail maintains its green skin (a* = -0.6) and light pulp (L* = 71.8).

Table 8. Fruit color (pulp and skin) according to the CIE L*a*b* standard for apples of the eight varieties from three different sources

No*	Cultivar	Source	Pulp color L*	Pulp color a*	Pulp color b*	Skin color L*	Skin color a*	Skin color b*
1	'Golden Delicious'	Boz	77.4±4.6 g-i	3.3±0.2 ef	27.3±1.8 e-g	61.1±3.6 ef	5.5±0.5 a	22.4±1.4 ab
2		Cluj	76.8±4.5 f-j	4.7±0.3 hi	31.4±2.1 k-m	71.8±4.1 f	4.7±0.6 a	31.4±1.9 a-d
3		Retail	75.0±4.6 d-g	2.7±0.2 de	29.8±1.9 i-l	56.0±2.3 de	4.7±0.4 a	41.4±2.1 d
4	'Jonathan'	Boz	77.5±4.2 g-j	3.1±0.3 d-f	28.7±1.7 f-i	43.3±2.1 b-d	15.9±0.9 bc	35.3±2.6 a-d
5		Cluj	77.2±3.9 g-j	3.0±0.4 d-f	26.7±1.8 d-f	45.7±2.0 b-e	19.6±0.8 c-e	30.1±2.1 a-d
6		Retail	77.5±4.1 g-j	3.0±0.2 d-f	29.6±2.1 h-k	44.2±2.1 b-d	24.5±1.5 c-f	35.9±2.3 a-d
7	'Florina'	Boz	75.1±4.3 d-h	4.1±0.3 gh	27.0±2.3 d-f	43.5±2.6 b-d	19.6±1.1 c-e	34.7±2.4 a-d
8		Cluj	78.2±4.2 ij	3.3±0.3 ef	20.3±1.5 a	52.0±3.1 c-e	27.4±1.3 d-f	34.3±2.8 a-d
9		Retail	75.0±4.6 d-g	3.5±0.4 fg	27.4±2.0 e-h	38.5±2.1 a-c	32.5±2.1 f	28.2±1.9 a-d
10	'Idared'	Boz	75.7±4.3 e-i	3.2±0.3 ef	23.8±1.4 bc	44.7±2.7 b-d	23.1±1.4 c-f	29.9±2.7 a-d
11		Cluj	79.1±4.2 j	3.1±0.2 d-f	26.7±1.6 d-f	49.4±2.9 c-e	28.9±1.7 ef	33.0±2.8 a-d
12		Retail	77.7±4.6 h-j	3.0±0.4 d-f	23.3±1.5 b	25.0±1.3 a	18.5±1.2 cd	21.0±1.4 a
13	'Starkrimson'	Boz	74.4±4.3 c-f	5.0±0.6 i	34.3±2.3 n	37.3±1.5 a-c	22.0±1.3 c-e	23.3±1.9 a-c
14		Cluj	72.8±4.2 b-d	6.4±0.7 j	34.3±2.1 n	32.7±1.7 ab	18.4±1.1 cd	24.2±1.7 a-c
15		Retail	71.5±3.8 ab	5.2±0.4 i	33.1±2.0 mn	37.6±1.6 a-c	16.8±0.8 c	23.3±2.1 a-c
16	'Fuji'	Boz	73.4±3.7 b-e	4.7±0.5 hi	31.2±1.9 j-m	50.6±2.4 c-e	17.0±0.9 c	38.2±2.6 b-d
17		Cluj	72.5±4.1 b-d	2.0±0.4 c	29.2±1.8 g-j	51.3±2.3 c-e	15.4±0.6 bc	39.4±2.7 cd
18		Retail	69.3±4.3 a	4.0±0.6 g	27.0±1.6 d-f	41.6±1.9 b-d	24.1±2.3 c-f	25.7±1.9 a-d
19	'Granny Smith'	Boz	71.3±3.7 ab	1.3±0.0 b	25.3±1.4 b-d	52.4±2.7 c-e	-4.0±0.3 ab	39.2±2.7 cd
20		Cluj	76.5±4.5 f-j	0.1±0.0 a	25.4±1.8 b-e	33.0±1.6 ab	6.5±0.7 ab	29.2±2.4 a-d
21		Retail	71.8±4.0 bc	-0.6±0.0 k	25.5±1.3 c-e	71.8±4.2 f	-0.6±0.0 ab	25.5±2.1 a-d
22	'Pinova'	Boz	73.5±4.1 b-e	7.1±0.9 k	21.8±1.6 lm	47.9±2.4 b-e	15.5±0.9 bc	34.0±2.8 a-d
23		Cluj	73.6±4.2 b-e	2.4±0.4 cd	27.5±1.4 e-h	43.2±2.1 b-d	20.1±1.3 c-e	31.8±2.1 a-d
24		Retail	73.6±4.3 b-e	3.5±0.6 fg	28.6±1.9 f-i	57.9±3.4 d-f	22.1±1.5 c-e	41.4±2.9 d

* 'Golden Delicious' fruits from the Boz orchard were obtained from the intensive orchard. According to Duncan's test ($\alpha < 0.05$), no significant difference exists between any two means in a column followed by the same letter for each trait.

The analysis of apple color reveals significant varietal differences in both pulp and skin color, independent of provenance (Table 9). 'Golden Delicious' exhibits a bright, yellowish pulp (L* = 76.4, b* = 29.5) and light, yellow-toned skin (L* = 62.9, b* = 31.7). 'Jonathan' and 'Florina' show similar pulp lightness but differ in skin color, with 'Florina' displaying a stronger red hue (a* = 26.5). 'Starkrimson' stands out with the darkest skin (L* = 35.8) and the most intense pulp coloration (a* = 5.5, b* = 34.1), while 'Granny Smith' is distinct for its greenish pulp (a* = 0.2) and skin (a* = 0.6). 'Fuji' and 'Pinova' exhibit balanced color profiles, with moderate lightness and pronounced red and yellow tones.

Table 9. Fruit color (pulp and skin) according to the CIE L*a*b* standard for eight apple varieties, irrespective of source of provenance

No*	Cultivar	Pulp color L*	Pulp color a*	Pulp color b*	Skin color L*	Skin color a*	Skin color b*
1	'Golden Delicious'	76.4±4.9 CD	3.6±0.2 BC	29.5±1.8 B	62.9±3.8 D	4.9±0.5 A	31.7±1.9 A
2	'Jonathan'	77.4±4.6 CD	3.0±0.1 B	28.3±1.7 B	44.4±2.3 A-C	20.0±1.2 B	33.8±2.4 A
3	'Florina'	76.1±4.7 C	3.6±0.4 C	24.9±1.6 A	44.7±2.7 A-C	26.5±2.7 C	32.4±2.1 A
4	'Idared'	77.5±3.8 D	3.1±0.3 BC	24.6±1.7 A	39.7±2.1 AB	23.5±2.3 BC	28.0±1.8 A
5	'Starkrimson'	72.9±3.1 AB	5.5±0.8 E	34.1±1.6 C	35.8±1.5 A	19.1±2.8 B	23.7±1.2 A
6	'Fuji'	71.7±4.6 A	3.6±0.4 BC	29.1±1.8 B	47.8±2.3 BC	18.8±1.8 B	34.4±1.1 A
7	'Granny Smith'	73.2±4.8 B	0.2±0.0 A	25.3±1.2 A	52.4±2.8 C	0.6±0.0 A	31.3±1.8 A
8	'Pinova'	73.6±4.0 B	4.3±0.6 D	29.3±2.1 B	49.7±2.6 BC	19.2±1.5 B	35.7±1.7 A

* 'Golden Delicious' fruits from the Boz orchard were obtained from the intensive orchard. According to Duncan's test ($\alpha < 0.05$), no significant difference exists between any two means in a column followed by the same letter for each trait.

Variations in pulp and skin color of apples were also recorded between the three sources of origin per ensemble of the eight apple varieties (Table 10). Apples from the Boz orchard exhibit the highest pulp lightness (L* = 74.8) and a more pronounced red tone (a* = 4.0) compared to those from Cluj-Napoca and retail sources. The yellow component (b*) of the pulp remains relatively consistent across all sources (≈27.8–28.6). Skin color shows minimal variation in lightness (L* ≈ 46.6–47.6) and yellow tone (b* ≈ 30.4–32.1) but differs in red intensity. Apples from retail establishments and Cluj-Napoca orchard display stronger red hues (a* ≈ 17.8 and 17.6, respectively) compared to those from the Boz orchard (a* = 14.3).

Table 10. Fruit color (pulp and skin) according to the CIE L*a*b* standard for apples from three sources of origin across eight varieties

No*	Orchard	Pulp color L*	Pulp color a*	Pulp color a*	Skin color L*	Skin color a*	Skin color b*
1	Boz orchard	74.8± 4.5 B	4.0±0.3 B	28.6±1.7 B	47.6±2.9 A	14.3±0.8 A	32.1±2.1 A
2	Cluj-Napoca orchard	75.8±4.2 C	3.1±0.1 A	27.8±2.0 A	47.4±2.1 A	17.6±0.9 B	31.7±1.9 A
3	Retail establishment	73.9±4.9 A	3.0±0.3 A	28.1±2.3 AB	46.6±2.8 A	17.8±1.3 B	30.4±1.6 A

* 'Golden Delicious' fruits from the Boz orchard were obtained from the intensive orchard. According to Duncan's test ($\alpha < 0.05$), no significant difference exists between any two means in a column followed by the same letter for each trait.

Fruit quality assessed through organoleptic analysis utilizing hedonic evaluation scales

The data in Table 11, obtained through organoleptic assessment on a hedonic scale, reveal significant variability in external fruit characteristics—size, shape, and color—across eight apple varieties and their three sources of origin. 'Golden Delicious' from the Boz orchard scores highest in size and shape, while its color scores moderately. In contrast, 'Golden Delicious' from Cluj-Napoca shows lower scores across all traits, particularly in size, suggesting that growing conditions significantly influence fruit appearance. 'Jonathan' exhibits high color scores, especially from the Boz orchard, but its size and shape scores are more variable, with retail-sourced fruits scoring lowest in size. 'Florina' and 'Idared' show similar trends, with Boz orchard fruits generally scoring higher in size and color, while Cluj-Napoca and retail sources lag behind. 'Starkrimson' stands out for its exceptional color scores, particularly from the retail, despite lower size scores across all sources. 'Fuji' and 'Granny Smith' display moderate scores, with 'Fuji' from the Boz orchard scoring lowest in color, indicating potential varietal limitations in this trait. 'Pinova' consistently scores high across all characteristics, regardless of origin, with color scores ranging from 8.0 to 8.3, underscoring its commercial appeal.

Table 11. Average scores for external fruit characteristics that contribute to commercial appearance obtained through organoleptic assessment on a hedonic scale from 1 to 9 (variety x source of origin interaction)

No*	Cultivar	Orchard/ Source	Fruit size	Fruit shape	Fruit color
1	'Golden Delicious'	Boz	8.8±0.5 h	8.2±0.4 f	7.5±0.4 c-e
2		Cluj-Napoca	6.2±0.3 d	7.6±0.7 e	7.0±0.5 bc
3		Retail	7.7±0.4 ef	7.2±0.4 cd	7.2±0.3 cd
4	'Jonathan'	Boz	6.3±0.2 d	6.5±0.3 a	8.5±0.5 fg
5		Cluj-Napoca	6.4±0.3 d	7.5±0.4 de	7.2±0.5 cd
6		Retail	5.5±0.1 c	7.2±0.7 cd	7.1±0.3 b-d
7	'Florina'	Boz	8.2±0.5 f-h	7.7±0.4 e	7.7±0.4 c-f
8		Cluj-Napoca	5.3±0.4 c	6.2±0.3 a	7.2±0.5 cd
9		Retail	6.5±0.2 d	6.3±0.4 a	7.4±0.4 c-e
10	'Idared'	Boz	8.7±0.5 gh	7.0±0.4 bc	7.2±0.4 cd
11		Cluj-Napoca	5.3±0.2 c	6.5±0.2 a	6.0±0.3 a
12		Retail	8.4±0.4 f-h	6.5±0.5 a	6.2±0.2 ab
13	'Starkrimson'	Boz	4.3±0.4 b	6.8±0.3 b	7.2±0.4 cd
14		Cluj-Napoca	3.5±0.2 a	7.6±0.7 e	8.0±0.7 d-f
15		Retail	4.3±0.4 b	7.7±0.3 e	9.0±0.6 g
16	'Fuji'	Boz	7.3±0.5 e	6.8±0.4 b	5.5±0.2 a
17		Cluj-Napoca	5.3±0.4 c	7.0±0.3 bc	7.0±0.5 bc
18		Retail	8.5±0.5 gh	7.2±0.4 cd	7.0±0.4 bc
19	'Granny Smith'	Boz	8.2±0.4 f-h	8.0±0.5 f	7.3±0.3 c-e
20		Cluj-Napoca	5.3±0.2 c	7.5±0.3 de	7.0±0.5 bc
21		Retail	5.3±0.3 c	7.5±0.4 de	7.0±0.5 bc
22	'Pinova'	Boz	8.2±0.5 f-h	8.0±0.5 f	8.0±0.4 d-f
23		Cluj-Napoca	8.5±0.4 gh	8.1±0.7 f	8.2±0.7 e-g
24		Retail	8.0±0.5 fh	8.0±0.4 f	8.3±0.5 e-g

* 'Golden Delicious' fruits from the Boz orchard were obtained from the intensive orchard. According to Duncan's test ($\alpha < 0.05$), no significant difference exists between any two means in a column followed by the same letter for each trait.

The data in Table 12, derived from organoleptic assessments on a hedonic scale, provide an overview of the external fruit characteristics—size, shape, and color—for eight apple varieties, irrespective of their provenance. 'Golden Delicious' scores highly in size (7.6 ± 0.5) and shape (7.7 ± 0.7), with moderate color scores (7.2 ± 0.6), reflecting its consistent commercial appeal. 'Jonathan' shows balanced scores, with a notable emphasis on color (7.6 ± 0.7), suggesting strong visual attractiveness despite slightly lower size (6.1 ± 0.4) and shape (7.1 ± 0.6) ratings. 'Florina' and 'Idared' exhibit moderate scores across all traits, with 'Idared' showing the lowest color score (6.5 ± 0.4), potentially limiting its marketability. 'Starkrimson', while scoring lowest in size (4.0 ± 0.6), achieves the highest color score (8.1 ± 0.9), highlighting its exceptional visual appeal despite smaller fruit dimensions. 'Fuji' and 'Granny Smith' display moderate performance, with 'Fuji''s color score (6.5 ± 0.4) aligning with 'Idared', indicating room for improvement in this trait. 'Pinova' stands out as the top-performing variety, achieving the highest scores in size (8.2 ± 0.9), shape (8.0 ± 0.9), and color (8.1 ± 0.7), underscoring its superior commercial appearance. In conclusion, while varieties like 'Pinova' and 'Golden Delicious' excel in external characteristics, others such as 'Starkrimson' and 'Idared' show trade-offs between size and color.

Table 12. Average scores for external fruit characteristics that contribute to commercial appearance obtained through organoleptic assessment on a hedonic scale from 1 to 9, for eight apple varieties regardless of their provenance

No*	Cultivar	Fruit size	Fruit shape	Fruit color
1	‘Golden Delicious’	7.6±0.5 E	7.7±0.7 D	7.2±0.6 BC
2	‘Jonathan’	6.1±0.4 B	7.1±0.6 B	7.6±0.7 C
3	‘Florina’	6.7±0.6 CD	6.7±0.4 A	7.4±0.5 BC
4	‘Idared’	7.5±0.5 E	6.7±0.5 A	6.5±0.4 A
5	‘Starkrimson’	4.0±0.6 A	7.4±0.7 C	8.1±0.9 D
6	‘Fuji’	7.0±0.5 D	7.0±0.4 B	6.5±0.4 A
7	‘Granny Smith’	6.3±0.4 BC	7.7±0.6 D	7.1±0.6 B
8	‘Pinova’	8.2±0.9 F	8.0±0.9 E	8.1±0.7 D

* ‘Golden Delicious’ fruits from the Boz orchard were obtained from the intensive orchard. According to Duncan's test ($\alpha < 0.05$), no significant difference exists between any two means in a column followed by the same letter for each trait.

The data in Table 13, obtained through organoleptic evaluation on a hedonic scale, highlight the influence of origin on external fruit characteristics—size, shape, and color—across eight apple varieties. Apples from the Boz orchard achieve the highest scores in size (7.5 ± 0.5) and shape (7.4 ± 0.5), with color scores (7.4 ± 0.5) comparable to those from retail establishments. In contrast, fruits from the Cluj-Napoca orchard score lowest in size (5.7 ± 0.4) and shape (7.2 ± 0.6), though their color scores (7.2 ± 0.6) remain competitive. Retail-sourced apples show intermediate size scores (6.8 ± 0.5) but match Boz orchard fruits in color (7.4 ± 0.4), suggesting that post-harvest handling or storage conditions may enhance visual appeal.

Table 13. Average scores for external fruit characteristics that contribute to commercial appearance obtained through organoleptic evaluation on a hedonic scale from 1 to 9, for apples from three sources of origin, across the ensemble of the eight varieties

No*	Orchard	Fruit size	Fruit shape	Fruit color
1	Boz orchard	7.5±0.5 C	7.4±0.5 B	7.4±0.5 A
2	Cluj-Napoca orchard	5.7±0.4 A	7.2±0.6 A	7.2±0.6 A
3	Retail establishment	6.8±0.5 B	7.2±0.7 A	7.4±0.4 A

* ‘Golden Delicious’ fruits from the Boz orchard were obtained from the intensive orchard. According to Duncan's test ($\alpha < 0.05$), no significant difference exists between any two means in a column followed by the same letter for each trait

The data in Table 14, obtained through organoleptic assessment on a hedonic scale, reveal significant variability in internal fruit characteristics. ‘Golden Delicious’ from the Boz orchard excels in aroma and consistency, while ‘Jonathan’ shows strong taste and aroma, particularly from the Boz orchard. ‘Florina’ achieves high pulp color and aroma but lacks consistency, whereas ‘Idared’ scores poorly in taste and aroma, indicating limited gustatory appeal. ‘Starkrimson’, despite high consistency, has low juiciness and taste, suggesting a texture-flavor trade-off. ‘Fuji’ and ‘Granny Smith’ display moderate performance, with ‘Fuji’ showing high consistency but lower taste. ‘Pinova’ stands out as the top performer, with exceptional scores in taste, aroma, juiciness, and pulp color, particularly from Cluj-Napoca and the retail.

Table 14. Average scores for internal fruit characteristics that contribute to intrinsic and gustatory quality obtained through organoleptic assessment on a hedonic scale from 1 to 9 (variety x source of origin interaction)

No*	Cultivar	Orchard/ Source	Pulp color	Consistency	Juiciness	Taste	Aroma
1	'Golden Delicious'	Boz	7.8±0.7 f-i	7.7±0.4 b-e	6.8±0.5 c-e	7.5±0.7 e	8.0±0.9 f-h
2		Cluj-Napoca	6.2±0.7 bc	7.8±0.7 b-e	6.5±0.3 bc	7.0±0.6 b-e	6.5±0.6 c-e
3		Retail	6.5±0.6 b-e	7.8±0.3 b-e	6.5±0.7 bc	7.2±0.4 c-e	6.2±0.7 cd
4	'Jonathan'	Boz	7.0±0.4 b-g	7.2±0.6 b	6.8±0.3 c-e	7.7±0.9 e	8.2±0.9 gh
5		Cluj-Napoca	7.6±0.5 e-i	7.8±0.5 b-e	8.0±0.7 f	7.5±0.7 e	7.3±0.4 e-g
6		Retail	5.0±0.4 a	5.8±0.6 a	7.4±0.9 ef	7.5±0.5 e	7.1±0.5 d-f
7	'Florina'	Boz	8.0±0.9 g-i	5.8±0.3 a	7.3±0.6 d-f	7.8±0.6 e	8.0±0.9 f-h
8		Cluj-Napoca	7.4±0.7 d-h	7.5±0.4 b-d	6.0±0.4 b	6.3±0.3 a-d	6.5±0.4 c-e
9		Retail	7.1±0.5 b-h	7.7±0.6 b-e	6.1±0.6 bc	6.3±0.4 a-d	6.5±0.5 c-e
10	'Idared'	Boz	6.7±0.4 b-f	7.0±0.6 b	6.6±0.4 b-d	6.0±0.3 ab	5.3±0.4 ab
11		Cluj-Napoca	6.3±0.6 b-d	5.8±0.6 a	7.3±0.8 d-f	6.0±0.7 ab	6.3±0.5 cd
12		Retail	6.1±0.3 b	5.2±0.3 a	7.5±0.7 ef	6.1±0.3 a-c	6.1±0.6 bc
13	'Starkrimson'	Boz	7.0±0.7 b-g	9.0±0.6 f	5.3±0.3 a	5.5±0.4 a	5.0±0.3 a
14		Cluj-Napoca	7.3±0.6 c-h	7.2±0.8 b	6.3±0.8 bc	7.0±0.8 b-e	7.3±0.7 e-g
15		Retail	7.1±0.5 b-h	7.4±0.6 bc	6.3±0.6 bc	7.4±0.6 de	7.1±0.6 d-f
16	'Fuji'	Boz	6.3±0.3 b-d	9.0±0.7 f	6.5±0.5 bc	5.8±0.7 a	6.2±0.8 cd
17		Cluj-Napoca	7.2±0.6 b-h	7.9±0.8 b-e	6.6±0.8 b-d	6.3±0.5 a-d	6.0±0.5 bc
18		Retail	7.2±0.7 b-h	7.7±0.6 b-e	6.6±0.7 bc	6.3±0.7 a-d	6.2±0.3 cd
19	'Granny Smith'	Boz	7.3±0.6 c-h	8.5±0.5 d-f	7.8±0.7 f	6.3±0.6 a-d	6.3±0.6 cd
20		Cluj-Napoca	7.0±0.6 b-g	8.6±0.8 ef	7.5±0.5 ef	7.5±0.6 e	7.3±0.6 e-g
21		Retail	7.0±0.5 b-g	8.0±0.5 b-f	7.5±0.8 ef	7.2±0.3 c-e	7.1±0.3 d-f
22	'Pinova'	Boz	8.2±0.8 hi	8.5±0.7 d-f	7.5±0.3 ef	7.8±0.8 e	8.3±0.9 h
23		Cluj-Napoca	8.5±0.7 i	5.4±0.5 a	8.0±0.8 f	9.0±0.5 f	8.6±0.7 h
24		Retail	8.5±0.9 i	8.4±0.7 c-f	9.0±0.6 g	9.0±0.6 f	8.6±0.9 h

* 'Golden Delicious' fruits from the Boz orchard were obtained from the intensive orchard. According to Duncan's test ($\alpha < 0.05$), no significant difference exists between any two means in a column followed by the same letter for each trait.

An overview of the internal characteristics of apple varieties' fruits, regardless of origin, presented in Table 15, shows that 'Golden Delicious' scores moderately on all traits, with consistency and taste being its strongest attributes. 'Jonathan' excels in juiciness, taste, and aroma, indicating strong gustatory appeal. 'Florina' achieves high pulp color but moderate scores in other traits, while 'Idared' scores lowest in taste and aroma. 'Starkrimson' shows low juiciness, and 'Fuji', despite high consistency, scores poorly in taste and aroma. 'Granny Smith' performs well in consistency and juiciness, with balanced scores in other traits. 'Pinova' stands out as the top performer, achieving the highest scores in juiciness, taste, and aroma, underscoring its superior intrinsic and gustatory quality.

Table 15. Average scores for internal fruit characteristics that contribute to intrinsic and gustatory quality obtained through organoleptic assessment on a hedonic scale from 1 to 9, for eight apple varieties regardless of their provenance

No*	Cultivar	Pulp color	Consistency	Juiciness	Taste	Aroma
1	'Golden Delicious'	6.8±0.5 BC	7.8±0.7 D	6.6±0.5 B	7.2±0.6 D	6.9±0.5 C
2	'Jonathan'	6.5±0.4 AB	6.9±0.5 B	7.4±0.7 CD	7.6±0.7 E	7.5±0.8 D
3	'Florina'	7.5±0.8 D	7.0±0.6 B	6.5±0.5 B	6.8±0.4 BC	7.0±0.6 C
4	'Idared'	6.4±0.5 A	6.0±0.5 A	7.1±0.6 C	6.0±0.5 A	5.9±0.5 A
5	'Starkrimson'	7.1±0.9 C	7.9±0.4 D	6.0±0.4 A	6.6±0.4 B	6.5±0.4 B
6	'Fuji'	6.9±0.5 C	8.2±0.9 E	6.6±0.8 B	6.1±0.5 A	6.1±0.5 AB
7	'Granny Smith'	7.1±0.7 C	8.4±0.7 E	7.6±0.5 D	7.0±0.4 CD	6.9±0.6 C
8	'Pinova'	8.4±0.7 E	7.4±0.5 C	8.2±0.7 E	8.6±0.9 F	8.5±0.8 E

* 'Golden Delicious' fruits from the Boz orchard were obtained from the intensive orchard. According to Duncan's test ($\alpha < 0.05$), no significant difference exists between any two means in a column followed by the same letter for each trait

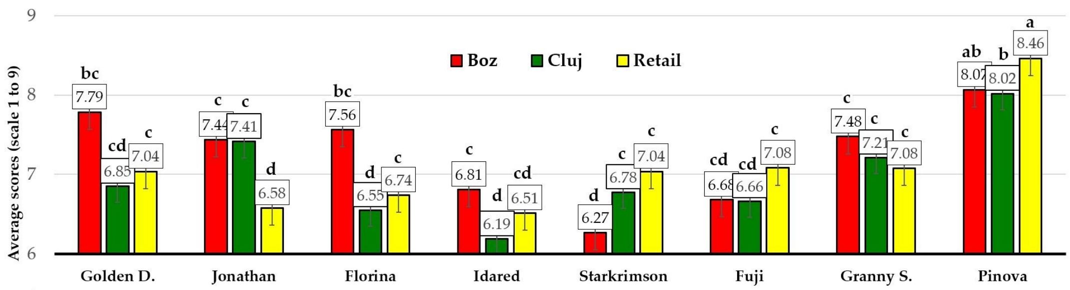
From Table 16, it follows that apples from the Boz orchard achieve the highest scores in pulp color and consistency, while their juiciness, taste, and aroma are moderate. Fruits from the Cluj-Napoca orchard show slightly lower pulp color and consistency but comparable juiciness, taste, and aroma. Retail-sourced apples exhibit similar trends, with slightly lower pulp color but improved juiciness and taste.

Table 16. Average scores for internal fruit characteristics that contribute to intrinsic and gustatory quality obtained through organoleptic assessment on a hedonic scale from 1 to 9, for apples from three sources of origin, across the ensemble of the eight varieties

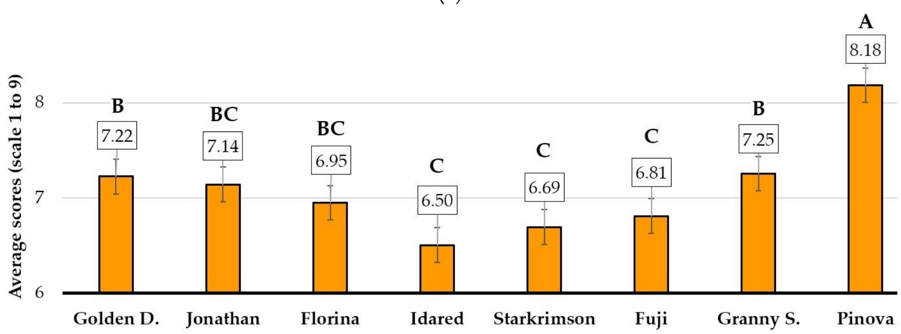
No*	Orchard	Pulp color	Consistency	Juiciness	Taste	Aroma
1	Boz orchard	7.3±0.5 B	7.8±0.5 A	6.8±0.4 A	6.8±0.8 A	6.9±0.5 A
2	Cluj-Napoca orchard	7.2±0.9 B	7.3±0.6 A	7.0±0.6 AB	7.1±0.7 A	7.0±0.7 A
3	Retail establishment	6.8±0.5 A	7.3±0.7 A	7.1±0.9 B	7.1±0.6 A	6.9±0.4 A

This ch* 'Golden Delicious' fruits from the Boz orchard were obtained from the intensive orchard. According to Duncan's test ($\alpha < 0.05$), no significant difference exists between any two means in a column followed by the same letter for each trait.

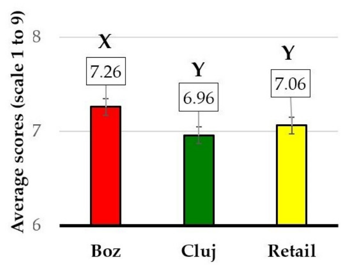
The analysis of average scores pertaining to the overall quality of fruits reveals significant variability, influenced by factors such as varieties, sources of origin, and their interaction (Figure 3). Notably, the differences in quality scores are particularly pronounced when comparing fruits of the same variety sourced from distinct origins. This trend is especially evident in the 'Idared' and 'Starkrimson', as well as in 'Jonathan' and 'Florina' (Figure 3a). For instance, in the case of 'Jonathan', fruits harvested from two specific orchards demonstrated superior quality compared to those obtained from the retail. In contrast, certain varieties exhibited greater consistency in quality scores across different sources. Specifically, 'Granny Smith' and 'Pinova' displayed a notable uniformity in their evaluations, suggesting that these varieties may be less susceptible to variations influenced by their origin. At the variety level, the 'Idared', 'Starkrimson', and 'Fuji' varieties received comparatively lower scores, indicating potential limitations in their overall quality as perceived by evaluators (Figure 3b). Conversely, 'Pinova' emerged as the most favorably assessed variety, reflecting its superior quality and appeal to tasters. When considering the sources of origin (Figure 3c), the Boz orchard consistently yielded fruits with the highest quality scores, and apples sourced from the Cluj-Napoca orchard received the lowest average scores.



(a)



(b)



(c)

Figure 3. The average scores for the overall quality of fruits, assessed on the hedonic evaluation scale with scores ranging from 0 to 9: (**a**) Depending on the eight apple varieties and the three sources of origin of the fruits; (**b**) Depending on the varieties across all sources of origin; (**c**) Depending on the sources of origin of the fruits across all eight varieties

'Golden Delicious' fruits from the Boz orchard were obtained from the intensive orchard. According to Duncan's test ($\alpha < 0.05$), no significant difference exists between any two means in a column followed by the same letter for each trait

Across the three sources of apple provenance, the organoleptic analysis revealed relatively minor percentage differences in the contribution of various elements that influence both the commercial appearance and intrinsic value of the fruits. These differences were observed at the level of individual varieties as well as in the specific characteristics pursued. To quantify these contributions, the eight key attributes evaluated using a sensory hedonic scale (ranging from 1 to 9) were transposed into percentage values. This approach highlighted the following variations in the contribution of each attribute, as a contribution from the overall fruit quality of 100% (Figure 4): fruit size: 7.6-16.1%; fruit shape: 11.7-13.7%; fruit color: 11.9-16.0%; pulp color: 9.5-13.2%; consistency: 10.0-14.3%; juiciness: 11.2-14.4%; taste: 11.1-14.3%; aroma: 10.9-13.5%. Within the varieties, the highest variation among sensory attributes was recorded for the 'Starkrimson', between fruit size (7.6%) and fruit color (16.0%). 'Pinova', on the other hand, showed the least variation, ranging from 11.8% for fruit size to 13.3% for juiciness and taste.

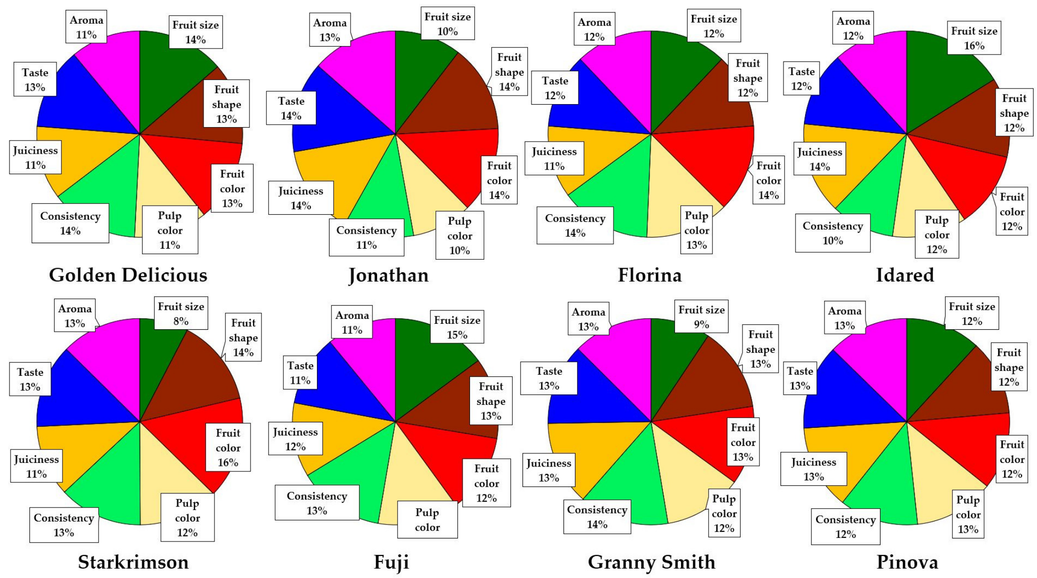
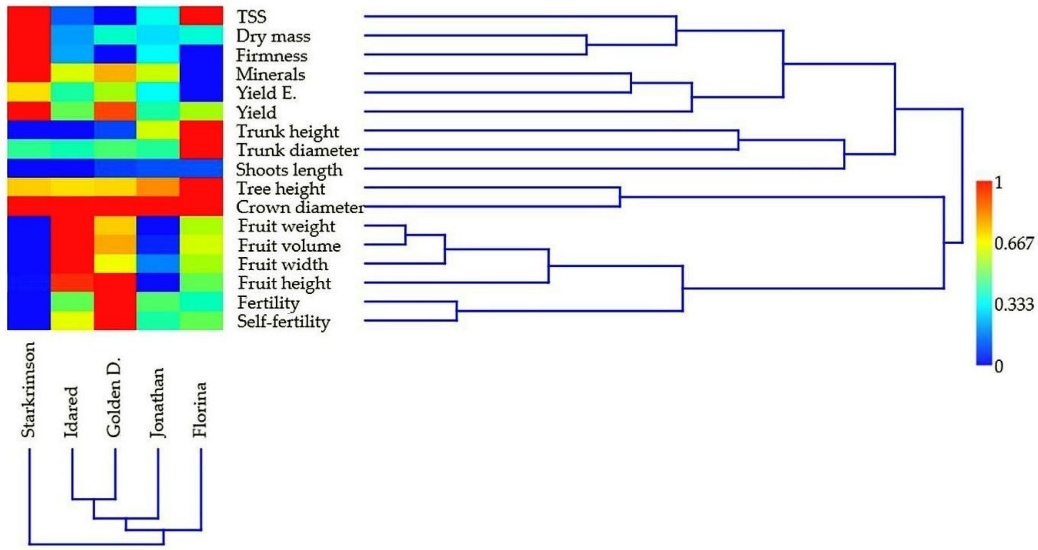


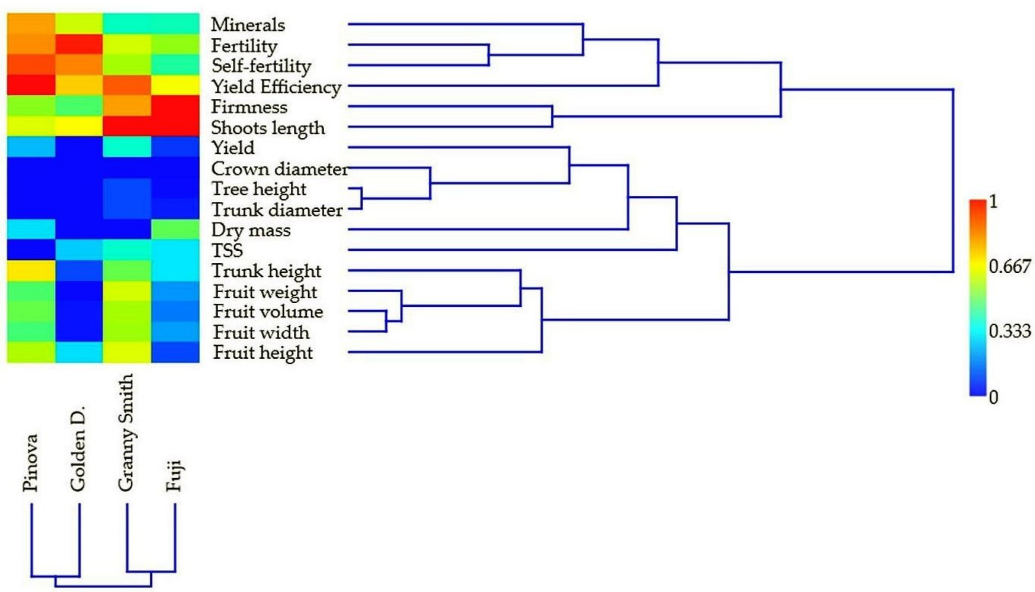
Figure 4. Contribution in percentage values of organoleptic characteristics to the overall evaluation of fruit quality (considered 100%) with the hedonic sensory evaluation system for eight apple varieties

Complexity of features and their interactions revealed through multivariate analyses

The hierarchical cluster analysis depicted in Figure 5, conducted separately for the intensive and super-intensive orchards, reveals several commonalities in the horizontal dendrogram concerning the analyzed characteristics. The analysis demonstrates strong associations between tree growth parameters, as evidenced by their grouping within shared clusters, as well as between the primary fruit characteristics, which are similarly clustered in close proximity. In the intensive orchard, the most closely related characteristics are fruit weight and fruit volume, which form a distinct pair. These two attributes are further grouped within a common subcluster that includes fruit width and fruit height. A comparable pattern is observed in the super-intensive orchard, where the physical and morphological attributes of the fruits also exhibit strong relationships. However, in this case, the closest association is between tree height and trunk diameter. These two growth parameters form a pair within a subcluster, which is further connected to an additional branch incorporating tree diameter. Notably, all these vigor-related elements are grouped within a shared subcluster that also includes fruit production. This implies a potential correlation between tree growth and production levels in the young super-intensive orchard. In both orchard systems, fertility and self-fertility are closely linked, forming a distinct pair within their respective subclusters. Interestingly, in the intensive orchard, these fertility traits are grouped within a subcluster that also includes fruit characteristics. Conversely, in the super-intensive orchard, fertility and self-fertility are clustered alongside fruit mineral content and yield efficiency, indicating a different pattern of association. Fruit firmness exhibits distinct relationships in the two orchards. In the intensive orchard, it is associated with dry matter content, while in the super-intensive orchard, it is linked to shoot length. This divergence highlights potential differences in how fruit quality and vegetative growth interact across the two systems.



(a)



(b)

Figure 5. Hierarchical clustering analyses (UPGMA) using Ward's method and Euclidean similarity index for the main analyzed characteristics of trees and fruits in apple varieties from two orchards with different cultivation systems: (**a**) intensive; (**b**) super-intensive

The vertical dendrogram further elucidates the relationships between apple varieties within each orchard. In the intensive orchard, 'Idared' and 'Golden Delicious' are positioned in proximity, while 'Starkrimson' is distinctly separated from the other varieties. In the super-intensive orchard, the analysis reveals two primary pairs: 'Pinova' and 'Golden Delicious', and 'Granny Smith' and 'Fuji'. The heat map analysis reveals distinct patterns in trait distribution across the intensive and super-intensive orchards. In the intensive orchard, cool colors (blue and green) dominate for the 'Starkrimson' variety, indicating low values for fruit characteristics, fertility, and self-fertility. This suggests underperformance in these traits compared to other varieties. Conversely, 'Starkrimson' shows warm colors (red and yellow) for sugar content (Brix), dry matter, mineral content, fruit firmness, fruit production, and production efficiency, highlighting its superior performance in these areas. This contrast underscores 'Starkrimson''s dual profile: weaker in morphological and fertility traits but stronger in fruit quality and yield-related metrics.

In the PCA in Figure A2 (a, b, c, d), the morphological elements of the apples, pulp and skin color, firmness and TSS, dry matter, Brix sugar and mineral content, as well as the sensory score evaluation elements, do not reveal clear similarities between apple varieties based on their origin or provenance. The most variables affecting fruit size for the apple cultivars grown in the Cluj-Napoca orchard are primarily found in quadrant 4 (Figure A2 a). This is likely attributable to the reduced size of the fruits, resulting from limited fertilization in the orchard, which primarily had an educational purpose rather than producing. If in Figures A2 b and A2 d it is difficult to identify a pattern, the analysis of firmness and chemical elements (Figure A2 c) shows that the three sources of fruit are closely grouped only for the 'Starkrimson' (located in quadrant 1) and 'Golden Delicious' (located in quadrant 3). However, 'Florina' apples from the Cluj-Napoca orchard, particularly those sourced from Boz, are positioned at a considerable distance and on an opposite diagonal compared to 'Florina' apples purchased from retail sources. The closest chemical components of the fruit were dry matter and Brix sugar, which, together with fruit firmness, ranked in the upper quadrant. In the second quartile, the minerals in the fruit were distinctly positioned, but similarly, on the right vertical axis.

Pearson phenotypic correlations indicate strong positive or negative relationships between different characters analyzed in the apple varieties from the Boz orchard (Figure A3). Significant correlations were recorded between different elements of tree growth, as well as between those of fruit size. Yield efficiency was negatively correlated with three elements of tree growth (height, trunk diameter and crown diameter), and self-fertility and natural fertility were negatively correlated with total soluble solids content and fruit color. A negative correlation was also identified between pulp consistency and fruit juiciness, while among the important characteristics of fruit quality, apple aroma and taste were positively correlated.

Discussion

The current study provided interesting information about tree growth and fruit yield and quality characteristics of apple varieties in intensive and super-intensive cropping systems. Significant differences were observed in tree growth between the two systems, attributed to the younger age of the super-intensive orchard and the inherent constraints of high-density planting. Among cultivars, 'Florina' in the intensive system and 'Granny Smith' in the super-intensive system exhibited the highest vigor, with superior tree height and trunk diameter.

Yield characteristics varied significantly between cultivars and systems. In the intensive orchard, 'Starkrimson' and 'Golden Delicious' had the highest fruit production, while 'Granny Smith' led in the super-intensive system. Yield efficiency, a relevant indicator of yield per unit of trunk cross-sectional area which strongly depends on many factors (Fioravanço *et al*., 2016; Plavcová *et al*., 2022; Robinson *et al*., 1991b), was highest for 'Starkrimson' in the intensive system and 'Pinova' in the super-intensive system. Self-fertility and natural fertility also varied, with 'Golden Delicious' showing the highest self-fertility in both systems and the highest natural fertility. 'Fuji' exhibited the lowest fertility values in the super-intensive system. The results underscore the impact of cultivation systems and variety selection on tree growth and productivity, as previously demonstrated in many studies (Hester and Cacho, 2003; Ho *et al*., 2024; Robinson, 2011).

The super-intensive system, while yielding smaller trees, demonstrated potential for efficient space utilization and higher shoot growth, which may contribute to long-term productivity. The higher yield efficiency (a composite parameter influenced by tree vigor and yield induced by the genotype of cultivar and rootstock, spacing, training and pruning, environmental and cultivation interaction system, etc.) in the high-density orchard confirmed that this system may support higher overall fruit production (Fioravanço *et al*., 2016; Ladon *et al.*, 2024; Robinson *et al*., 1991a; Srivastava *et al*., 2017). Yield variability among varieties confirms the importance of selecting appropriate varieties for specific cropping systems to optimize productivity and resource efficiency (Hampson *et al*., 2009; Murphy *et al*., 2007; Nedeljković *et al*., 2023). Further research should explore long-term performance and economic viability to inform orchard management strategies. The findings indicated that the analyzed apples had a variable chemical content, including mineral content, indicating that the differences may be due to the genotype (variety), the ecological and technological conditions in which the fruits were obtained, regional variations, the time of harvest or testing, etc. (Er and Ozcan, 2010; Francini *et al*., 2022; Ličina *et al*., 2024; Mészáros *et al.*, 2021; Mota *et al*., 2022; Natić *et al*., 2024)

Although the investigation did not encompass all intended research directions, the findings offer valuable insights into the effects and influences of cultivar selection and plantation systems on certain productive and qualitative traits, as observed in the analysis conducted in the Boz orchard. Pearson correlations revealed relationships between various aspects of tree growth and efficiency, some of which were unexpected but can be useful for orchard management. Successful high-density orchards that guarantee substantial and yearly yields, together with superior fruit quality, under economically efficient conditions, necessitate a comprehensive understanding of all affecting factors and their interrelationships, as well as judicious decision-making (Hester and Cacho, 2003; Majid *et al.*, 2018; Phillips, 2005; Wertheim *et al*., 2001b). A more robust comparison could have been achieved through a study design ensuring identical conditions across plantations, such as shared varieties, uniform cultivation systems and technologies, orchards of the same age, trees grafted onto the same rootstock, and consistent treatment applications. Such conditions would have established an objective framework for comparison. While the 'Golden Delicious' cultivar was present in both plantations, the study focused exclusively on the quality characteristics of fruits from the intensive plantation. Initially, it was deemed methodologically unsound to compare these results with those from the super-intensive plantation. Nevertheless, such a comparison might have yielded insights into potential similarities or differences in fruit quality for the same variety under identical pedoclimatic conditions but differing cultivation systems or technologies. Due to the absence of a viable framework for a meaningful comparative analysis, the study did not emphasize direct comparisons between the two orchards. Instead, the research prioritized a comparative analysis of different varieties and the three distinct origins of the fruits. Although the analytical and sensory evaluations were conducted uniformly and consistently, the determinations made in the first decade of October may have introduced some variability due to differences in the ripening stages among cultivars. This variability underscores the importance of considering temporal factors in future studies to ensure more precise and reliable comparisons.

However, apple quality is influenced by multiple variables, including cultivar and growing environment (Kaack and Pedersen, 2010; Pereira-Lorenzo *et al*., 2009; Roussos and Gasparatos, 2009; Zhang *et al*., 2018). The analyzed study highlighted significant differences in fruit size, color, and firmness, essential elements for consumer acceptability. Compared to the existing literature, Musacchi and Serra (2018) emphasized the importance of agronomic and environmental factors in determining quality parameters, such as soluble sugar content and acidity. Argenta *et al*. (2022) demonstrated that the cultivation environment affects apple firmness and biochemical composition, confirming that apples grown at higher altitudes exhibit superior firmness and a higher concentration of bioactive compounds. In addition, not only the variety but also the rootstock can influence the chemical composition of the fruit (Butkeviciute *et al*., 2022; Fallahi *et al*., 1985).

The chemical composition of apples analyzed in the current study revealed significant differences among cultivars, with 'Starkrimson' showing the highest dry matter and sugar content. Similar results were reported by Mignard *et al.* (2021), who found that genetic adaptation and climatic conditions influence antioxidant levels and overall antioxidant capacity in apples. Furthermore, Milosevic *et al.* (2022) highlighted the impact of fertilization on polyphenol and flavonoid content, suggesting that agricultural practices can be optimized to enhance the nutritional value of apples. Additionally, recent studies demonstrated that genetic differences among cultivars could lead to variations in fiber, mineral, and vitamin content, contributing to the health benefits of apples (Doğan *et al.*, 2024).

Hedonic evaluation of apple quality is crucial for understanding consumer preferences. The analyzed study showed that 'Pinova' and 'Golden Delicious' were the most appreciated varieties, aligning with Gatti *et al.* (2011), who demonstrated that sweetness, aroma, and crisp texture are key factors in consumer selection. Likewise, Seppä et al. (Seppä *et al.*, 2013) found that the definition of an ideal apple varies based on individual perceptions, but firmness and balance between sweetness and acidity remain consistent in general preferences. The study by Hampson *et al.* (2000) confirms the significance of sensory methods in selecting the most favored apple varieties, indicating that consumer perceptions of taste and texture influence purchasing and consumption decisions.

Comparing these findings with the literature, there is a clear convergence of data indicating that agricultural practices and growing environments play a determining role in shaping apple characteristics. Additionally, sensory analysis has proven to be an essential tool in quality evaluation, providing valuable insights for producers and retailers. Improving cultivation methods and carefully selecting varieties could enhance apple market competitiveness (Doğan *et al.*, 2024; Hampson *et al.*, 2000). Furthermore, the integrated use of sensory analysis could improve the selection and commercial promotion of the most viable apple varieties (Akagic and Oras, 2025; Gatti *et al.*, 2011).

Sensorial analyses are indispensable in apple breeding, particularly for the selection and promotion of new varieties. However, while our study has demonstrated the reliability of sensory testing in differentiating apple quality through scoring, thereby proving its applicability for the qualitative discrimination of varieties, we cannot assert that this reliability extends to the use of such tests in the breeding process. Consequently, we contend that sensory tests employing a 1-to-9 scale for all external characteristics contributing to commercial appearance, as well as for intrinsic quality attributes of apples, are not the most suitable for use in the selection and promotion of hybrids or clonal selections in advanced stages of the breeding process. A compelling argument against the appropriateness of hedonic tests using a 1-to-9 scale is the fact that a sample (genotype—hybrid, clonal selection, etc.) may achieve a very high overall score if it receives the maximum rating for seven out of eight fruit quality attributes, even if its taste is notably poor. Conversely, in apple breeding and selection, a hybrid stands no chance of being selected as elite or promoted to advanced stages if the fruit's taste is not exceptional. Therefore, a differentiated scoring scale, with variable weights assigned according to the paramount considerations in breeding, is far more appropriate for analyzing fruit quality. For instance, a scale with scores ranging from 1 to 3 for fruit size and shape, as well as pulp color and texture, from 1 to 5 for fruit color, juiciness, and aroma, and from 1 to 15 for taste, used in previous studies (Dan *et al.*, 2015a; Morariu *et al.*, 2025), would more accurately reflect the differences in the contribution of essential traits to the advancement of genotypes in the breeding process. Such a nuanced approach would better align with the priorities of apple breeding, ensuring that key attributes like taste are given the emphasis they deserve.

Conclusions

This study provides valuable insights into the influence of cultivar selection and production conditions on apple quality, highlighting the complexity of interactions between genetic, environmental, and orchard management factors. The findings confirm that apple quality is not solely determined by genetic characteristics but is significantly shaped by cultivation practices and ecological conditions. By integrating morphological, biochemical, and organoleptic analyses, the research underscores the importance of a holistic approach in assessing fruit quality. A major contribution of this study is the comparative analysis of apples grown under intensive and super-intensive systems. The results indicate that while super-intensive orchards maximize space utilization and enhance productivity, they also impose physiological constraints on trees due to increased planting density. This trade-off manifests in differences in tree vigor, fruit size, and biochemical composition. Notably, the highest fruit production in the intensive system was recorded for 'Starkrimson' and 'Golden Delicious', whereas 'Granny Smith' yielded the most in the super-intensive system. Furthermore, 'Pinova' emerged as the most efficient variety in terms of yield efficiency, reinforcing its suitability for high-density plantations. These findings are significant for orchard management, demonstrating that appropriate cultivar selection can optimize production and ensure sustainability. The biochemical composition of apples revealed substantial variability among cultivars and growing conditions. 'Starkrimson' exhibited the highest dry matter and sugar content, suggesting a stronger metabolic response to environmental factors. Similarly, differences in mineral content, firmness, and total soluble solids reflect the impact of soil composition, fertilization, and irrigation. The study corroborates previous findings that cultivation systems influence apple quality beyond visual and morphological attributes, affecting the nutritional and commercial value of the fruit. The organoleptic evaluation demonstrated that consumer perception of apple quality is multifaceted, influenced by appearance, texture, taste, and aroma. 'Pinova' and 'Golden Delicious' were the most appreciated varieties, aligning with studies emphasizing the importance of sweetness, crispness, and balance between acidity and sugar content. The variability observed across different sources of origin further confirms the role of ecological and technological factors in determining consumer preferences. This highlights the need for consistent quality control measures in apple production and marketing. From a methodological perspective, the study emphasizes the relevance of integrating quantitative and sensory analyses in apple research. However, the results suggest that a more refined scoring system, with weighted evaluation criteria, would enhance the accuracy of quality assessments, particularly in apple breeding programs. While the 1-to-9 hedonic scale provides valuable consumer insights, it may not fully capture the complexity of quality determinants in apple selection processes. Overall, the study contributes to a deeper understanding of apple production and quality, offering practical implications for breeding, orchard management, and market optimization. Future research should focus on long-term performance assessments, including the impact of climate change on apple production. Additionally, exploring genetic and molecular markers could facilitate the development of cultivars with improved resilience and enhanced nutritional properties. By integrating agronomic innovation with consumer-driven preferences, sustainable apple production can be achieved while ensuring high-quality fruit for the market.

Authors' Contributions

Conceptualization, A.E.M., V.M. and R.E.S.; methodology, A.E.M. and A.F.S.; software, A.F.S. and C.D.; validation, M.M. and V.M.; formal analysis, P.A.M., A.F.S. and C.D.; investigation, P.A.M.; resources, A.E.M., A.F.A. and O.B.; data curation, A.F.A., O.B. and M.M.; writing—original draft preparation, P.A.M. and A.F.S.; writing—review and editing, A.E.M., V.M. and R.E.S.; visualization, A.F.S., C.D., A.F.A., O.B. and M.M.; supervision, A.E.M., M.M. and R.E.S.; project administration, A.E.M., C.D. and V.M.; funding acquisition, P.A.M. and A.E.M. All authors read and approved the final manuscript.

Ethical approval (for researches involving animals or humans)

Not applicable.

Acknowledgements

This research was supported partly by the University of Agricultural Sciences and Veterinary Medicine from Cluj-Napoca (USAMVCN), through the Doctoral School for P.A.M., and by the Ministry of Agriculture and Rural Development, through the project ADER 2026, 6.1.4/18/07/2023.

Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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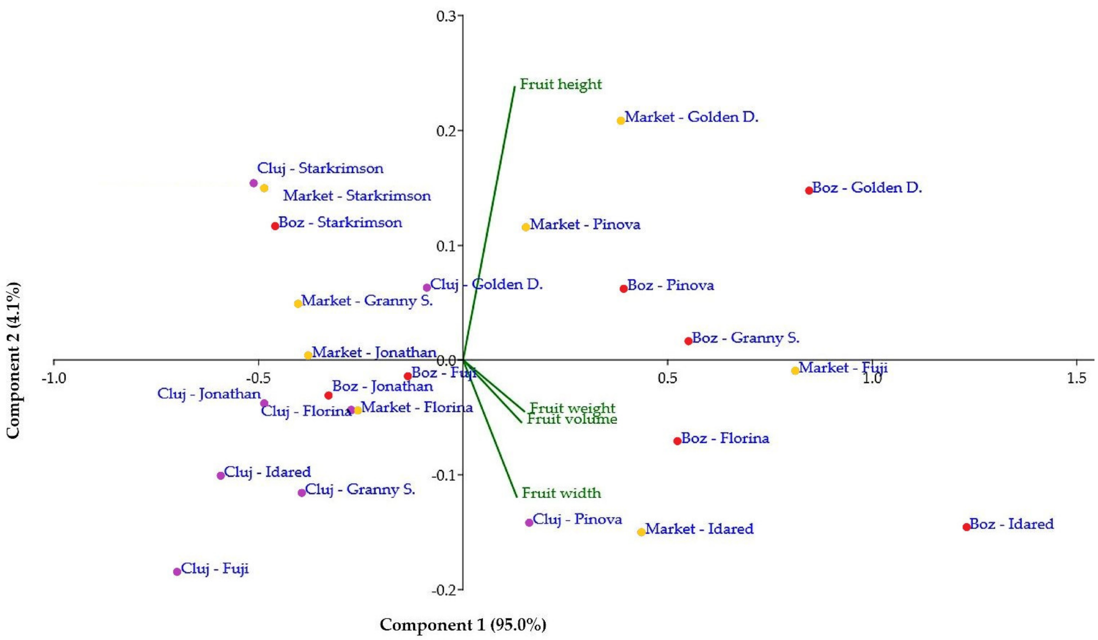
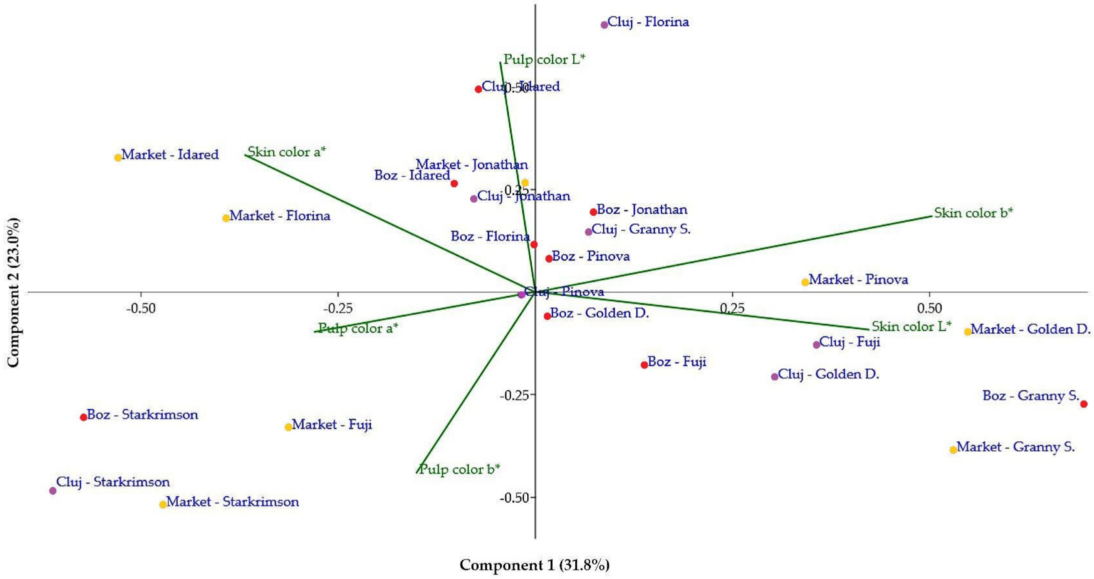
Appendix

1. (**a**) 2. (**b**) 3. (**c**) 4. (**d**) 5. (**e**) 6. (**f**) 7. (**g**) 8. (**h**)

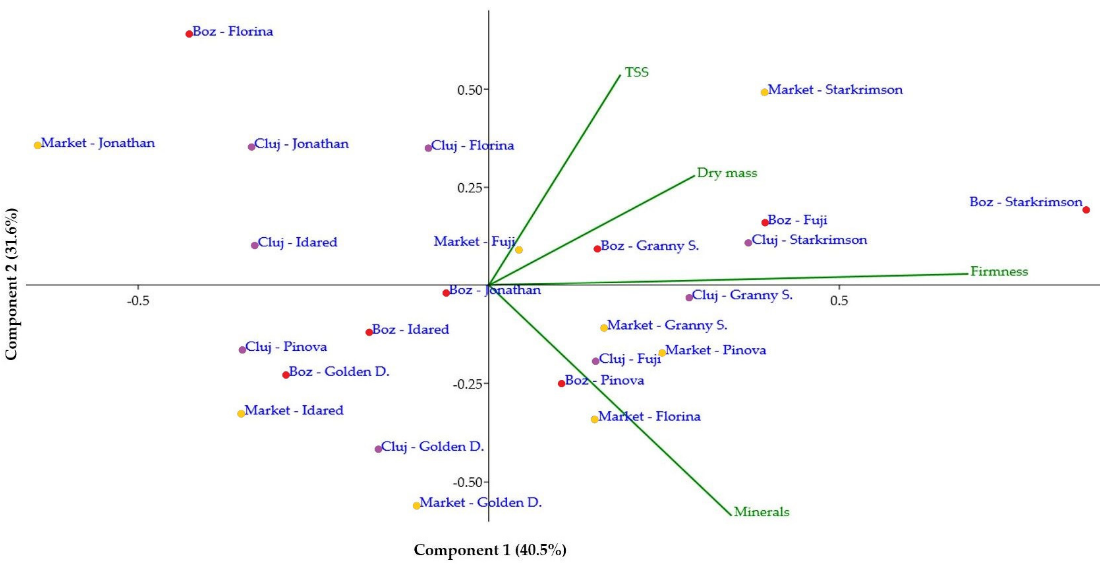
Figure A1. The fruits of the varieties from the Boz orchard: (**a**) 'Golden Delicious'; (**b**) 'Jonathan'; (**c**) 'Florina'; (**d**) 'Idared'; (**e**) 'Starkrimson'; (**f**) 'Fuji'; (**g**) 'Granny Smith'; (**h**) 'Pinova'.



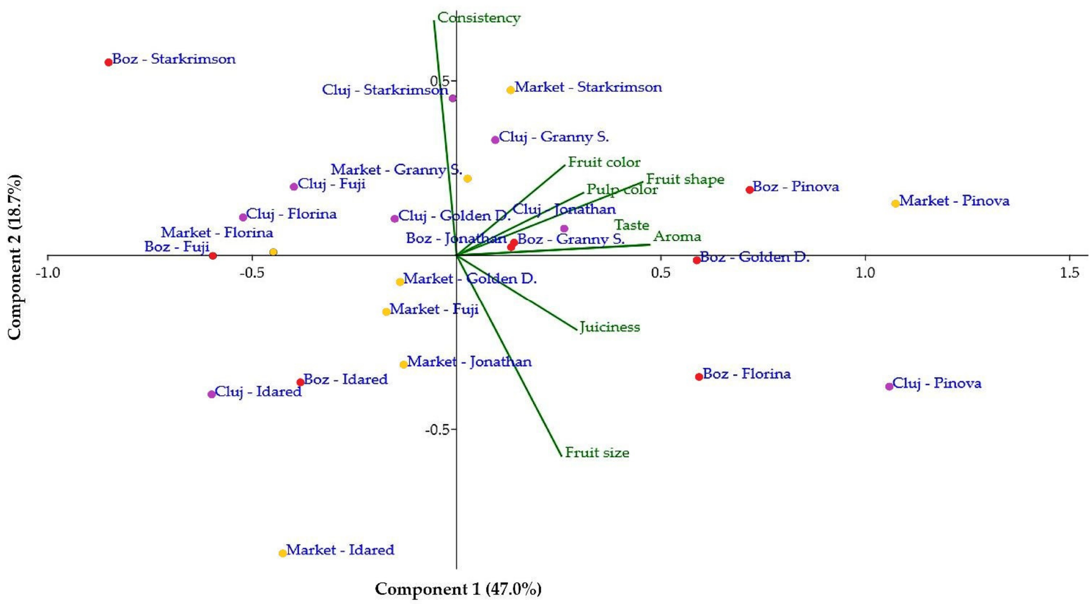
(**a**)


Cluj - Florina
Pulp color L*
Cluj - Idared
Market - Idared
Skin color a*
Market - Jonathan
Boz - Idared
Cluj - Jonathan
Boz - Jonathan
Skin color b*
Market - Florina
Cluj - Granny S.
Boz - Florina
Boz - Pinova
Market - Pinova
Cluj - Pinova
Pulp color a*
Boz - Golden D.
Skin color L*
Market - Golden D.
Cluj - Fuji
Boz - Fuji
Cluj - Golden D.
Boz - Granny S.
Boz - Starkrimson
Market - Fuji
Market - Granny S.
Pulp color b*
Cluj - Starkrimson
Market - Starkrimson
-0.50
-0.25
0.25
0.50
Component 2 (23.0%)
Component 1 (31.8%)

(**b**)


Boz - Florina
TSS
Market - Starkrimson
Market - Jonathan
Cluj - Jonathan
Cluj - Florina
Dry mass
Boz - Starkrimson
Boz - Fuji
Cluj - Idared
Market - Fuji
Boz - Granny S.
Cluj - Starkrimson
Firmness
Boz - Jonathan
Cluj - Granny S.
Market - Granny S.
Boz - Idared
Cluj - Pinova
Market - Pinova
Cluj - Fuji
Boz - Golden D.
Boz - Pinova
Market - Idared
Market - Florina
Cluj - Golden D.
Market - Golden D.
Minerals
0.50
0.25
-0.5
0.5
-0.25
-0.50
Component 2 (31.6%)
Component 1 (40.5%)

(**c**)



(**d**)

Figure A2. Principal component analysis (PCA) of apple varieties analyzed for the main fruit characteristics depending on their provenance: (**a**) morphological traits of fruits; (**b**) pulp and skin color of fruit; (**c**) fruit firmness and chemical elements in fruits; (**d**) organoleptic of fruits

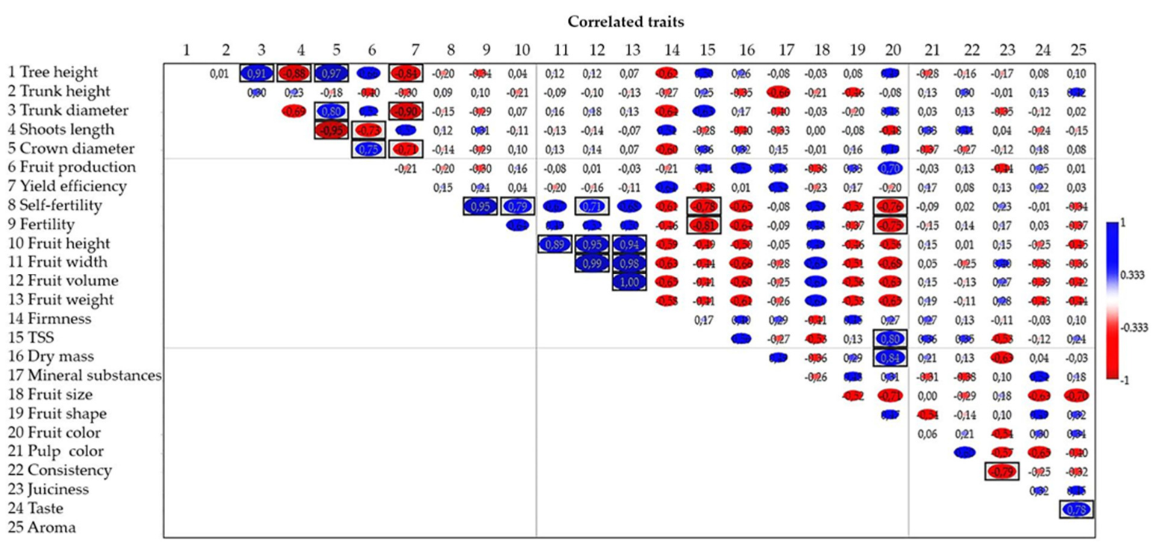


Figure A3. Pearson correlations between the characteristics analyzed in the apple va-rieties from the Boz orchard, except for the 'Golden Delicious' from the super-intensive orchard. Positive correlations are represented in blue, while negative correlations are depicted in red. The color intensity and the circle's size are proportionate to the correlation coefficients. The grey background boxes represent the significant values at $p < 0.05$ (two-tailed)