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PhD THESIS

Evaluation of interesting traits of different apple varieties and possibilities for their use in breeding

(SUMMARY OF Ph.D. THESIS)

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INTRODUCTION

The apple (*Malus domestica* Borkh.) is one of the most important fruit species globally, with a wide distribution in temperate regions. Due to its high ecological adaptability and phenotypic plasticity, it is cultivated from the cold regions of Asia to subtropical zones (STROHM, 2023). Global production exceeds 57 million metric tons annually, with over 60 countries contributing to this volume, with China, the U.S., and European nations leading as top producers (FAOSTAT, 2023).

From a horticultural perspective, the apple has versatile uses: fresh consumption, industrial processing (juices, jams, cider, vinegar), long-term storage, and ornamental purposes (SEPPA et al., 2013; TEH et al., 2021). It is also a powerful cultural symbol, present in various mythologies and traditions. The cultivated apple is the result of a complex hybridization and selection process, with its primary origin in Central Asia. The wild species *Malus sieversii*, from the Tian Shan Mountains (Kazakhstan), is recognized as the ancestor of the domesticated apple (SESTRAȘ & SESTRAȘ, 2023). Genetic studies confirm its essential role in domestication, a process accelerated by ancient trade routes such as the Silk Road (JUNIPER et al., 1998; BROWN, 2012).

The varietal diversity is impressive - between 6,000 and 15,000 cultivars - yet the global market is dominated by a few commercial varieties such as 'Golden Delicious', 'Gala', 'Fuji', and 'Granny Smith'. In recent decades, breeding efforts have focused on developing modern cultivars with disease resistance, high sensory quality, and technological performance. A notable example is 'Crimson Snow', an internationally successful variety prized for its appearance, taste, and excellent storage behavior. Cytogenetically, most cultivars are diploid ($2n = 34$), but there are also triploids ($2n = 3x = 51$) that influence fertility and vigor (SESTRAȘ, 2004; ȘTEFAN, 2013).

The taxonomy of the *Malus* genus remains complex, and recent sequencing studies contribute to clarifying phylogenetic relationships. Beyond commercial aspects, the apple plays a vital role in healthy nutrition, providing antioxidants and fiber, and supports sustainable ecosystems. In the context of climate change and market demands, advanced genetic breeding is crucial for maintaining the relevance of this species in global horticulture (SESTRAȘ, 2004).

Crabapples, or ornamental apples, are also known for their decorative value. Their floral display, attractive foliage, and architectural tree ideotype make ornamental varieties widely appreciated and used in parks and urban green spaces (TITIRICĂ et al., 2023; DAN et al., 2015).

STRUCTURE OF THE THESIS. MATERIAL AND METHOD

The PhD thesis entitled *“Evaluation of interesting traits of different apple varieties and possibilities for their use in breeding”* is structured into three main parts, totaling 160 pages, and contains 8 chapters, 31 tables, 35 figures, and 203 bibliographical references, both national and international. The **first part** of the thesis provides a comprehensive literature review of the current state of knowledge in apple cultivation and breeding. This section is structured into five chapters and offers a thorough synthesis of relevant information from specialized literature. Chapter 1 discusses the economic, social, and nutritional importance of apples as a fruit species, highlighting cultivar diversity and the continuous need to develop new varieties adapted to market demands and climate challenges. Chapter 2 is dedicated to the origin and genetic diversity centers of apples, presenting the evolution of *Malus domestica* and the contribution of wild species to the genetic base of modern cultivars. It emphasizes genetic resources usable in breeding and essential biological traits for conservation and selection. Chapter 3 covers priority objectives in apple breeding, such as productivity, fruit quality (color, shape, taste), disease resistance (scab, powdery mildew), pest resistance, adaptability to different climatic conditions, flowering and ripening periods, and frost resistance. Chapter 4 focuses on breeding methods applicable to the species, from classical intra- and interspecific hybridization to mutagenesis and modern biotechnologies, including molecular markers. Chapter 5 provides an integrative perspective on apple breeding and underscores the importance of conserving genetic resources for the future of sustainable orchard management. The **second part** of the thesis presents the personal contribution and is structured into three chapters, detailing the research aims and objectives, the natural environment where experiments were conducted, the biological material and experimental conditions, and the analysis of traits of interest in apple breeding. The **third part** includes the results obtained from three experiments. In the first experiment were studied tree characteristics based on the cultivation system, yield depending on cultivar and cultivation system, morphological fruit traits by cultivar and origin, firmness, color, and biochemical fruit characteristics by cultivar and three sources, fruit quality results from organoleptic analysis using a hedonic evaluation scale, and multivariate analysis of trait complexity and interactions. In the second experiment were examined the physicochemical properties of fruits, multivariate analysis results, and organoleptic properties of 34 apple cultivars from the germplasm collection of the Research-Development Institute for Pomology Pitești-Mărăcineni (ICDPP). In the third experiment was investigated the incidence of apple pathogens and pests during the growing season, infection rates, infestation levels across six studied orchards and cultivars, and the relationship between biotic stress factors, environmental conditions,

and management practices. The thesis concludes with chapter 8, which highlights the originality and innovative contributions of the research.

The findings have been disseminated through three scientific articles published in ISI-indexed journals.

The research conclusions provide an important contribution to the selection of apple genotypes with breeding potential, offering applicable data for future hybridization programs and the introduction of new cultivars into cultivation.

RESULTS AND DISCUSSIONS

The findings from the **first experiment** provided interesting insights into the varying quality of fruits, influenced both by cultivar and origin within the same cultivar (due to cultivation conditions, ecological factors, and multiple interactions between variables, among others). The study yielded relevant results regarding tree growth, production traits, and fruit quality in apple cultivars grown in the same location but under different cultivation systems- intensive and super-intensive. Significant differences in tree growth were observed between the two systems, attributed to the younger age of the super-intensive orchard and the inherent constraints of high-density planting. Among the 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 traits varied significantly between cultivars and systems. In the intensive orchard, 'Starkrimson' and 'Golden Delicious' had the highest fruit production, while 'Granny Smith' stood out in the super-intensive system. Yield efficiency, a key parameter influenced by tree vigor, genotype, rootstock, planting density, training, pruning, and environmental interactions, 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. Conversely, 'Fuji' recorded the lowest fertility values in the super-intensive system. These results highlight the impact of cultivation systems and cultivar selection on tree growth and productivity, consistent with previous studies.

The super-intensive system, despite producing smaller trees, demonstrated high potential for efficient space utilization and increased shoot growth, which may contribute to long-term productivity. The higher yield efficiency in the high-density orchard confirmed that this system can sustain greater total fruit production. The variability in yield among cultivars underscores the importance of selecting suitable cultivars for specific cultivation systems to optimize productivity and resource efficiency. Further research should explore long-term performance and economic viability to inform orchard management strategies. The analyzed apples exhibited

variable chemical composition, including mineral content, suggesting that differences may arise from genotype (cultivar), ecological and technological conditions, regional variations, harvest timing, or testing procedures, among other factors. Although the study did not cover all proposed research directions, the results provide valuable perspectives on the effects of cultivar selection and planting systems on production and quality traits, as observed in the Boz orchard analysis. Pearson correlations revealed relationships between different aspects of tree growth and efficiency, some unexpected but useful for orchard management. High-density orchard systems that deliver substantial annual yields while maintaining premium fruit quality under economically viable conditions demand a thorough comprehension of all involved factors and their complex interactions, coupled with informed strategic decision-making.

A more robust comparison could have been achieved through a study design ensuring identical conditions across orchards, such as using the same cultivars, uniform cultivation systems and technologies, orchards of the same age, trees grafted on the same rootstock, and consistent treatment applications. Such conditions would have established an objective framework for comparison. Although 'Golden Delicious' was present in both orchards, the study focused solely on fruit quality traits in the intensive system. Initially, a methodological comparison with the super-intensive system was deemed unreliable. However, such a comparison could have provided insights into potential similarities or differences in fruit quality for the same cultivar under identical pedoclimatic conditions but different 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 cultivars and the three distinct fruit origins.

Although analytical and sensory evaluations were conducted uniformly and consistently, assessments performed in the first decade of October may have introduced some variability due to differences in cultivar ripening stages. This variability underscores the importance of accounting for temperature factors in future studies to ensure more precise and reliable comparisons. Apple quality is influenced by multiple variables, including cultivar and growing environment. The analyzed study highlighted significant differences in fruit size, color, and firmness, key factors in consumer acceptability. Compared to existing literature, Musacchi & Serra (2017) emphasized the role of agronomic and ecological factors in determining quality parameters such as soluble sugar content and acidity. Argenta et al. (2022), demonstrated that growing environment affects apple firmness and biochemical composition, confirming that apples grown at higher altitudes exhibit superior firmness and higher concentrations of bioactive compounds. Furthermore, not only cultivar but also *rootstock* can influence fruit chemical composition. The chemical

analysis of apples in the current study revealed significant differences between cultivars, with 'Starkrimson' having the highest dry matter and sugar content. Similar findings were reported by Mignard et al. (2021), who found that genetic adaptation and climatic conditions influence antioxidant levels and total antioxidant capacity in apples. Additionally, Milosevic et al. (2022) highlighted the impact of fertilization on polyphenol and flavonoid content, suggesting that agricultural practices can be optimized to enhance nutritional value. Recent studies have also shown that genetic differences between cultivars may lead to variations in fiber, mineral, and vitamin content, contributing to the health benefits of apples.

Hedonic assessment of apple quality is essential for understanding consumer preferences. The analyzed study found that 'Pinova' and 'Golden Delicious' were the most appreciated cultivars, aligning with Gatti et al. (2011), who demonstrated that sweetness, aroma, and crisp texture are key factors in consumer selection. Seppä et al. (2013) noted that the definition of an "ideal apple" varies based on individual perceptions, but firmness and the balance between sweetness and acidity remain consistent in general preferences. Hampson et al. (2000) confirmed the importance of sensory methods in selecting the most favored apple cultivars, indicating that consumer perceptions of taste and texture influence purchasing and consumption decisions. Comparing these findings with the literature reveals a clear convergence of data indicating that agricultural practices and growing environments play a decisive role in shaping apple characteristics. Additionally, sensory analysis has proven to be an essential tool in quality assessment, providing valuable insights for producers and marketers. Improving cultivation methods and careful cultivar selection could enhance competitiveness in the apple market. Furthermore, the integrated use of sensory analysis could refine the selection and commercial promotion of the most viable apple cultivars.

Sensory analyses are indispensable in apple breeding, particularly for the selection and promotion of new cultivars. However, while this study demonstrated the reliability of sensory testing in differentiating apple quality through scoring, thus proving its applicability for qualitative discrimination among cultivars, we cannot assert that this reliability extends to the use of these tests in the breeding process itself. Consequently, we argue that sensory tests using a 1–9 scale for all external traits contributing to marketable appearance, as well as intrinsic quality attributes of apples, are not the most suitable for selecting and promoting hybrids or clonal selections in advanced breeding stages. A strong argument against the appropriateness of hedonic tests using a 1–9 scale is that a sample (genotype-hybrid, clonal selection, etc.) may receive a very high total score if it achieves maximum ratings in seven out of eight fruit quality attributes, even if its flavor is considerably poor. Conversely, in apple breeding and selection, a hybrid will have no chance of being selected as elite or promoted to advanced stages if its fruit flavor is not exceptional. Therefore, a differentiated scoring

scale, with variable weights assigned based on fundamental breeding priorities, is far more appropriate for fruit quality analysis. For example, a scale with 1–3 points for fruit size, shape, pulp color, and texture, 1–5 points for fruit skin color, juiciness, and aroma, 1–15 points for flavour, as used in previous studies, would more accurately reflect the differences in the contribution of essential traits to genotype advancement in breeding programs. Such a nuanced approach would better align with apple breeding priorities, ensuring that key attributes like flavor receive the emphasis they deserve.

The results obtained in the first experiment were published in an ISI-indexed journal with the following identification details:

Morariu PA, Mureșan AE, Sestraș AF, Dan C, Andrean AF, Borsai O, Militaru M, Mureșan V, Sestraș RE (2025). The impact of cultivar and production conditions on apple quality. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca* 53(1):14046. <https://doi.org/10.15835/nbha53114046>

In the second experiment, the examination of germplasm resources, encompassing 34 apple cultivars, revealed substantial variation among the studied genotypes in terms of organoleptic, biochemical, and morphological fruit traits. The study indicated considerable variability between cultivars for most fruit characteristics, a finding of significant interest for apple breeding, cultivation, and fruit utilization. For each analyzed trait, remarkable cultivars were identified based on superior values or attributes, enabling their targeted use for diverse purposes. It is well known that, depending on their characteristics, different cultivars may be better suited for specific fruit applications, including fresh consumption, domestic or industrial processing (e.g., baking, tarts, pies, jams, compotes, purees, juices, jellies, vinegar, cider, alcohol). Thus, cultivars highlighted for specific attributes can be primarily applied where they are most suitable.

The association of key morphological fruit traits (dimensions, shape, weight, volume) with sensory-appreciated attributes (size, shape, color) provided an overview of cultivars with commercially attractive appearance. Interestingly, among these cultivars were old varieties, including internationally recognized classics (e.g., ‘Jonathan’, ‘Kaltherer Böhmer’, ‘Golden Delicious’), as well as old Romanian cultivars. ‘Crețesc Auriu’, a clonal selection from a very old Romanian landrace (‘Crețesc’), is a notable example, dating back to the empirical apple breeding period. The high regard for certain classic international cultivars in Romania (e.g., ‘Jonathan’) and regional favorites like ‘Kaltherer Böhmer’ in parts of Transylvania likely reflects their strong adaptation to local environmental conditions. Additionally, their commercial quality enhanced by attractive appearance, intense and shiny fruit color particularly in long, sunny autumns with warm days and cool nights, is complemented by excellent flavor and aroma. Undoubtedly, the intrinsic fruit traits and their wide variation depend on

both genotype and environmental conditions, as well as genotype-environment interactions.

Both fruit epidermis characteristics and pulp texture, as well as biochemical composition, exhibited significant differences among the analyzed cultivars. Investigations into apple epidermis and texture revealed notable variation between cultivars in skin hardness, pulp firmness, fruit resistance. These traits may influence storage potential and consumer preferences.

The wide ranges observed for total soluble solids (10.6–20.7%), water and ash content, titratable acidity, total carotenoids (0.35–6.60 mg/100 g), were attributed to both genotypic differences (cultivar-specific traits) and the direct influence of ecological and technological conditions under which the fruits were grown. These factors can significantly alter chemical composition, likely explaining the discrepancies between various studies on apples for similar biochemical traits and the broad limits within which these values may fluctuate. Additional influences may arise from fruit maturity at harvest, storage duration before analysis, post-harvest handling conditions, analytical procedures and methodologies used. Nevertheless, the importance of apples for human health and their nutritional value is expressed not only through fresh fruit consumption but also through diverse processing and utilization methods. The classification of cultivars analyzed in this study into three main groups provided interesting insights and even some surprises when compared to an unstated but presumably obvious hypothesis. We expected to identify significant genetic progress between the three distinct cultivar groups representing different historical eras in apple breeding and cultivation. However, statistically significant differences were not found among these groups regarding the principal components contributing to overall apple quality. Surprisingly, it was not the group of modern cultivars that showed the best results for morphological, biochemical and sensory characteristics, but rather the group of classic international varieties originating predominantly from the 18th-19th centuries. This could be explained by these cultivars excellent adaptation to Romanian pedoclimatic conditions and, of course, by the fact that the analyzed cultivars represented only small samples from the vast number of apple varieties existing internationally.

Another objective of this study was to identify potential parental forms for new hybridization breeding efforts. Artificial hybridization remains one of the primary methods to generate the variability needed for selecting superior new genotypes and creating novel cultivars. The efficiency of new cultivar selection depends directly on the value of parental forms used in controlled crosses and the appropriate selection of maternal or paternal parents. Cultivar studies like ours, aimed at identifying potential parents with superior fruit quality and specific suitability, are crucial for successful apple breeding.

This study confirms the exceptional quality value of numerous cultivars from the classic international assortment, which continue to enjoy high appreciation and excellent quality ratings worldwide and in Romania. The 'Jonathan' cultivar is particularly widespread and valued among Romanian growers and consumers. Moreover, it has been used as a parental form in numerous artificial hybridizations, giving rise to new local cultivars. Many Romanian cultivars from the so-called 'modern era' of apple breeding, including some developed in Cluj-Napoca such as 'Aromat de vară', 'Ardelean', 'Feleac', 'Ancuța' and 'Roșu de Cluj', share 'Jonathan' as a common parent. 'Golden Delicious' is also highly valued and, unlike 'Jonathan', remains a fundamental cultivar in current Romanian orchards. Similar to 'Jonathan', 'Golden Delicious' has participated in complex hybridizations, often serving multiple times as a common parental form for the same new cultivars, such as 'Precoce de Ardeal' with its complex origin from the Fruit Research Station in Cluj-Napoca.

Such selection schemes demonstrate the complex processes of apple breeding and the multiple generations of hybridization or backcrossing and successive selection required to create a new variety. Simultaneously, they reflect the genetic narrowing of cultivars through excessive and repeated use of the world's highest-rated cultivars as parents. Additionally, the inevitable inbreeding occurring during selection processes and the strong selection pressure for generally common breeding objectives (yield, fruit quality, resistance to biotic and abiotic stressors) have contributed to the genetic narrowing of current cultivars and increased genetic vulnerability. Many traditional Romanian cultivars have lost the competition with international varieties. Some have disappeared completely, while others maintain only very limited distribution or are preserved as germplasm sources. Other cultivars that represented childhood apples for many generations in northwestern Transylvania proved to be poor parents when used in apple breeding programs. The 'Poinic' cultivar, once widespread in Transylvania but nearly extinct today, was famous for its flattened spherical green fruits with dense, firm and compact flesh. Children would traditionally hit these apples to soften them, the tough skin wouldn't break, but the inner flesh texture would rupture, filling the fruit with incredibly flavored juice. Unfortunately, our previous research demonstrated that 'Poinic' lacks the traits needed to be considered a valuable breeding parent, transmitting to its progeny excessive tree vigor, branched growth habit, disease susceptibility, particularly to apple scab, and other undesirable characteristics including poor fruit quality. Similar to 'Poinic', many old cultivars are underutilized due to their inferior fruit quality that often fails to meet evolving consumer and processor standards. Additionally, these cultivars exhibit other inferior biological characteristics such as vulnerability to pathogens and pests, inadequate production, biennial bearing, and tree habit unsuitable for intensive orchards. Nevertheless, they constitute a vital and dynamic genetic reservoir. Due to fruit appreciation and consumer nostalgia, 'Poinic' (along with other ancient cultivars) is

currently being propagated in some Transylvanian nurseries, though typically in small quantities for private gardens using seedling rootstocks. The qualitative attributes of 'Poinic', along with other traditional Romanian and classic international apple cultivars, highlight their suitability for fresh consumption, home processing, and cooking. Meanwhile, modern cultivars with their refined quality meet commercial fruit market requirements, while those richest in beneficial compounds are also ideal for industrial processing.

Multivariate analyses provide extremely useful information for apple breeding and selection of new parental forms to generate the variability needed for cultivar development. Moreover, multivariate data analysis approaches can successfully evaluate the sensory qualities and chemical profiles of apple cultivars. The identified correlations between traits of interest can provide valuable insights for apple breeding and cultivation. In apple breeding, phenotypic correlations, especially when complemented by genotypic correlations, can be used as selection indices. This allows for indirect selection where selection for one trait can be performed in tandem with another closely correlated trait of interest. A similar procedure can be applied for negatively correlated traits, where selection can be made against a trait that shows an inverse relationship with the desired characteristic.

PCA and hierarchical cluster analyses revealed some unexpected associations for fruit quality among cultivars with different historical and geographical origins, particularly surprising given how dissimilar these cultivars appeared in terms of both commercial appearance and sensory evaluation or recognition ('Sovari' with 'Jonathan'; 'Poinic' with 'Green Golden'; 'Patul' with 'Golden Delicious'). Data dimensionality reduction in the dendrogram, incorporating all analyzed characteristics including sensory attributes and overall organoleptic fruit evaluation, showed a limited number of closely related cultivars by origin. Among traditional Romanian cultivars, 'Domnesc' and 'Crețesc Auriu' showed a close relationship in a paired cluster. 'Cox's Orange Pippin' was associated with 'Wagener', while 'James Grieve' paired with 'Pearmain' among classic international cultivars. Among modern genotypes, 'Florina' and 'T194', as well as 'Elstar' and 'Judor', formed pairs. Interestingly, some close connections appeared between cultivars from different historical periods: 'Jonathan' (dating to 1826) paired with 'Golden Orange' (released in 1996 and based on the famous 'Golden Delicious'), while 'Kaltharer Böhmer' (likely originating from Bolzano, northern Italy before 1810) paired with 'Goldrush' (New Jersey, USA, introduced to market in 1994).

The dendrogram analysis based on all examined traits revealed significant overlap in clusters of morphological, biochemical, and sensory fruit attributes, emphasizing the importance of pulp characteristics, taste, aroma, and juiciness. Commercial appearance formed a distinct subcluster significantly associated with fruit color. The separation of color and appearance dendrograms from overall quality

provides crucial insights for apple quality evaluation and breeding, regardless of a hybrid's aesthetic appeal during selection, it cannot achieve cultivar status without exceptional organoleptic qualities, particularly superior taste.

The clustering of cultivars from different geographic origins and historical periods through multivariate analysis of numerous quality-contributing factors may contradict previously observed variability. Alternatively, this apparent variability at genotype level ranges might actually reflect the narrowing genetic base of cultivated apples and their shared ancestral origins, despite coming from different eras and temperate climate regions. This genetic bottleneck likely results from intensive historical selection for fruit size, superior taste, beneficial biochemical content, and nutritional value, all traits associated with resistance to biotic and abiotic stressors. Numerous studies highlight genetic erosion and vulnerability due to narrowing apple gene pools. Despite the impressive number of existing cultivars, their shared ancestry poses future risks. These threats are particularly acute in apples due to intensive selection for fruit quality traits, allogamy, heterozygosity, and vegetative propagation through grafting.

Modern super-intensive monoculture orchards with limited genetic diversity face heightened vulnerability to climatic risks, pests, and pathogens. Incorporating wild species in hybridization can enhance genetic diversity and stress resilience. The Fruit Research Station Cluj has implemented this methodology using various *Malus* species. Phenotypic selection can be integrated with molecular markers in breeding programs. However, using wild species significantly reduces fruit size and quality in progeny, necessitating prolonged selection in subsequent generations to restore these characteristics.

This study highlighted the fruit quality of numerous historically significant cultivars with national or global distribution. Due to tree longevity and vegetative propagation, many heritage cultivars remain commercially relevant. Traditional cultivars constitute a vital genetic reservoir for future breeding efforts. Future research should integrate molecular and genetic approaches to improve selection processes and ensure adaptability to changing climates and consumer preferences. Additional key research areas should include production performance, cultivation costs, ecological and cultural impacts on fruit quality, market requirements, pricing trends, consumer cultivar preferences, and emerging fruit industry directions. Understanding these aspects will provide valuable insights for developing strategies aligned with market dynamics and consumer expectations.

The results obtained in the second experiment were published in an ISI-indexed journal with the following identification details:

Morariu PA, Mureşan AE, Sestraş AF, Tanislav AE, Dan C, Mareşi E, Militaru M, Mureşan V, Sestraş RE (2025). A comprehensive morphological, biochemical, and

sensory study of traditional and modern apple cultivars. *Horticulturae* 11(3):264. <https://doi.org/10.3390/horticulturae11030264>

In the third experiment, the five-year study of five apple cultivars revealed consistent differences in biotic stress responses, determined by both genetic background and environmental conditions. Apple scab (*V. inaequalis*) showed significant cultivar and location variability, with infection strongly correlated with spring and early summer precipitation. This supports previous findings that leaf wetness duration and relative humidity are crucial for scab development. 'Golden Delicious' showed highest susceptibility, while 'Florina' maintained complete resistance conferred by the Rvi6 gene (formerly Vf), though isolated infections occurred in nearby poorly managed orchards. These results reinforce that resistant cultivars like 'Florina' can significantly reduce fungicide needs, offering economic and ecological benefits. Notably, scab response varied for identical genotypes depending on environmental and management conditions. 'Pinova' showed considerable susceptibility variability between orchards and years, explaining contradictory classifications in literature. Fungal disease management, particularly scab control, remains the most costly aspect of apple production, accounting for over 70% of phytosanitary treatments, with more than half targeting scab. The high treatment costs and potential yield losses exceeding 70% underscore the need for new cultivars combining robust resistance with superior commercial qualities. For powdery mildew (*P. leucotricha*), epidemiology differed with infection peaks under warm, dry conditions, particularly in Boz and Izvoru Ampoiului locations. 'Jonathan' and 'Idared' showed highest susceptibility, while 'Florina' again demonstrated excellent field resistance. Climate correlations confirm mildew incidence increases significantly in warmer years, aligning with projections of intensified pathogen activity under climate change. Regarding pests, codling moth (*C. pomonella*), woolly apple aphid (*E. lanigerum*), and aphids (*Aphis spp.*) proved most impactful. Infestation levels positively correlated with high temperatures, supporting observations that pest phenology accelerates in warm conditions. 'Florina' again showed high infestation tolerance, likely due to protective morphological or biochemical traits. High heritability (H^2) values for scab, mildew, and woolly aphid reinforce breeding efficiency for resistance. Moderate to low values for codling moth and bitter rot highlight the need for flexible, weather-risk-based management strategies.

This study provides original contributions by integrating disease and pest monitoring with multivariate climate data and heritability analysis. This approach enhances understanding of cultivar resilience and supports development of precision orchard systems better adapted to climate variability and less dependent on chemical inputs. The consistently superior performance of 'Florina' demonstrates the potential of genetically resistant cultivars to simultaneously achieve productivity and ecological sustainability goals. By combining field observations with ecological and genetic

interpretations, this work advances current knowledge of apple genotype adaptive performance under real cultivation conditions and provides a solid foundation for future breeding decisions, orchard design, and integrated pest management.

The results obtained in the third experiment were published in an ISI-indexed journal with the following identification details:

Morariu PA, Sestraş AF, Andrean AF, Borsai O, Bunea CI, Militaru M, Dan C, Sestraş RE. Apple cultivar responses to fungal diseases and insect pests under variable orchard conditions: a multisite study. *Crops* 2025, 5, 30. <https://doi.org/10.3390/crops5030030>

CONCLUSIONS AND RECOMMENDATIONS

The first experiment 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 results confirm that apple quality is not solely determined by genetic traits 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 in intensive and super-intensive systems. The findings indicate that while super-intensive orchards maximize space utilization and enhance productivity, they also impose physiological constraints on trees due to higher planting density. This trade-off manifests in differences in tree vigor, fruit size, and biochemical composition. Notably, the highest fruit yield in the intensive system was recorded for the ‘Starkrimson’ and ‘Golden Delicious’ cultivars, while ‘Granny Smith’ had the highest yield in the super-intensive system. Furthermore, the ‘Pinova’ cultivar proved to be the most efficient in terms of yield performance, reinforcing its suitability for high-density plantations. These results are significant for orchard management, demonstrating that proper cultivar selection can optimize production and ensure sustainability. The biochemical composition of apples revealed substantial variability between 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 confirms previous findings that cultivation systems influence apple quality beyond visual and morphological attributes, affecting nutritional and commercial value. The organoleptic evaluation demonstrated that consumer perception of apple quality is complex, influenced by appearance, texture, taste, and aroma. ‘Pinova’ and ‘Golden Delicious’ were the most appreciated cultivars, aligning

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with studies emphasizing the importance of sweetness, firmness, and the balance between acidity and sugar content. The observed variability among different origins further confirms the role of ecological and technological factors in shaping consumer preferences. This underscores the need for consistent quality control measures in apple production and marketing. From a methodological perspective, the study highlights the relevance of integrating quantitative and sensory analyses in apple research. However, the results suggest that a more refined evaluation system, incorporating weighted criteria, would improve the accuracy of quality assessments, particularly in apple breeding programs. While the 1–9 hedonic scale provides valuable consumer insights, it may not fully capture the complexity of factors determining apple quality in 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 evaluations, including the impact of climate change on apple production. Additionally, exploring genetic and molecular markers could facilitate the development of cultivars with enhanced resistance and improved nutritional properties. By integrating agronomic innovations with consumer preferences, sustainable apple production can be achieved while ensuring high-quality fruit for the market.

The second experiment provides a detailed analysis of 34 apple cultivars, including old Romanian varieties, internationally recognized classic and modern cultivars, as well as new selections. The results highlight significant morphological, biochemical, and organoleptic variability among these cultivars, emphasizing the importance of genetic diversity in apple breeding programs. From a morphological perspective, substantial differences were observed in fruit size, shape, and weight. While classic international cultivars exhibited the highest average values for these traits, Romanian native varieties displayed distinctive characteristics. However, the lack of statistically significant differences among the three major groups suggests that fundamental traits are maintained over time. Biochemical analysis revealed significant variations in moisture content, total soluble solids, titratable acidity, carotenoid levels, and mineral composition. Certain old Romanian and international cultivars demonstrated high-value biochemical profiles, making them suitable for both fresh consumption and processing. For example, cultivars such as ‘Reinette de Champagne’ and ‘Baujade’ showed high carotenoid content, enhancing their potential as functional foods with superior nutritional benefits. Additionally, variations in acidity and soluble solids influence the suitability of different cultivars for specific market demands and consumer preferences. Texture analysis showed notable variability in skin hardness, pulp firmness, and overall resistance, traits that affect storage and transport resilience. Furthermore, the organoleptic evaluation highlighted that cultivars such as ‘Golden Orange’, ‘Jonathan’, ‘Kaltharer Böhmer’, and ‘Golden Delicious’ stood out in terms of

aroma, texture, and consumer appeal. In conclusion, this study underscores the need to conserve and utilize both traditional and modern apple cultivars to maintain a diverse and resilient apple industry. The results provide essential data for breeding programs, orchard management, and market strategies, supporting fruit quality optimization and the preservation of valuable genetic resources.

The third experiment highlights the complex interactions between genetic, ecological, and cultivation factors that determine apple tree responses to major diseases and pests. Among the five analyzed cultivars, 'Florina' demonstrated the most consistent resistance to both pathogens and insect pests, while 'Jonathan' and 'Golden Delicious' were generally more susceptible. Disease incidence was strongly correlated with precipitation levels, whereas pest infestations showed a significant dependence on temperature. Multivariate and regression analyses revealed consistent co-occurrence patterns among certain biotic stressors, particularly between *E. lanigerum* and *Aphis spp.*, as well as between powdery mildew and scab. The calculated heritability coefficients confirmed that genetic factors substantially contribute to stress responses in most cases, suggesting that resistance breeding remains a viable and important objective. Integrating these findings emphasizes the need for location-specific management strategies that consider both cultivar resistance profiles and local environmental conditions. These insights are relevant for improving disease and pest forecasts, optimizing treatment programs, and selecting cultivars with the best adaptability to changing climatic scenarios.

INNOVATIVE CONTRIBUTIONS OF THE THESIS

The thesis provides original and relevant scientific contributions to the field of pomology by employing an integrated and multidisciplinary approach to evaluate apple quality in relation to genetic, ecological, and technological factors. A key innovative element is the comparative analysis of tree performance and fruit quality in both intensive and super-intensive cultivation systems. The study highlights the physiological trade-offs induced by high planting density and underscores the superiority of certain cultivars, such as 'Pinova', in high-density orchards, offering concrete recommendations for cultivar selection based on the applied technological system.

From a methodological perspective, the thesis proposes a differentiated sensory evaluation scale, assigning specific weights to traits such as taste, aroma, and texture, which are critical in advanced selection stages. This approach enables a more accurate discrimination of valuable genotypes, surpassing the limitations of classical hedonic scales typically used in consumer-oriented or commercial evaluations.

Another innovative contribution lies in the comprehensive characterization of a broad spectrum of 34 apple cultivars, including traditional, international, and modern selections, aiming to identify valuable parental forms for breeding. Multivariate analyses (PCA, dendrograms, correlation matrices) revealed unexpected associations between cultivars from different historical periods and geographical origins, indicating phenotypic convergence with potential relevance for assisted selection strategies.

Moreover, the integration of heritability analysis for traits related to resistance against biotic stressors (apple scab, powdery mildew, pests) under variable climatic conditions adds significant value in the direction of selecting resilient genotypes. These findings support the development of precision horticultural systems and contribute to reducing reliance on chemical inputs. Overall, the thesis offers a robust scientific foundation for apple breeding in the context of sustainable agriculture and ongoing climate change.

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Additional full-length contributions closely related to the subject of the doctoral research

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