ANNALS OF THE UNIVERSITY OF CRAIOVA

Series: ✓*Biology*
✓*Horticulture*
✓*Food products processing technology*
✓*Environmental engineering*

Vol. XXXI (LXVII) - 2026

IMPACT OF MECHANICAL CONTOUR RUNNING ON YIELD AND FRUIT QUALITY OF APPLE GRAFTED ON M9 ROOTSTOCK INTENDED FOR INDUSTRIAL PROCESSING

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Keywords: *apple, pruning, weight, yield.*

ABSTRACT

Labor shortages and the high costs of manual pruning are prompting fruit growers to adopt mechanical apple pruning, particularly for fruit intended for industrial processing. The research was carried out on the cultivars 'Champion', 'Golden Delicious', 'Golden Rezistent', and 'Pinova' (M9 rootstock, 4.0 x 1.2 m planting scheme). Mechanical contour pruning was performed in the spring on both sides of the canopy at angles of 12–13° and 4–5° relative to the vertical plane, maintaining a basal width of 150–180 cm. Both methods (mechanical and manual) reduced tree height to 3.0 m and canopy width to 2.0 m. The mechanical variant established a compact fruiting wall without compromising bearing capacity. Average fruit weight decreased moderately (from 110.13 g to 101.03 g), which was offset by high yield and economic efficiency. However, mechanical pruning requires manual follow-up detailing and rigorous fruit thinning.

INTRODUCTION

The cultivated apple is the primary fruit species of temperate zones and, alongside banana and orange, accounts for the largest share of global fruit production, ranking third worldwide (Balan et al., 2001, 2021). In the Republic of Moldova, apple remains the dominant fruit crop, representing over 60 % of the national pomological asset base and generating over 70 % of total fruit production, serving as a profitable and revenue-generating enterprise. With a bearing surface ranging between 43,000 and 45,000 hectares, the fruit sector has been undergoing a major technological transition over the past decade, characterized by a highly heterogeneous structure in terms of orchard age, training systems, and productivity (Cimpoieș, 2012; Babuc, 2012).

National average yield fluctuates between 10 and 13 t/ha; however, this figure masks vast discrepancies across orchard types. To revitalize the fruit sector and increase per-hectare yields, traditional cultivars (such as 'Idared' or 'Florina', which are heavily dependent on eastern export markets) are gradually being phased out in favor of high-yielding cultivars and clones of 'Gala', 'Fuji', and 'Red Delicious' (Cimpoieș et al., 2001; Bilici, 2020). Currently, approximately 40–50 % of the total orchard area consists of aged orchards older than 15–20 years. Due to high maintenance costs, low production, and depressed prices offered for processing

apples, these orchards have become unprofitable for fresh market export and are being grubbed up at an accelerated pace.

Traditional manual pruning is one of the most expensive and time-consuming field operations in pomiculture, requiring between 80 and 120 hours of labor per hectare performed by skilled workers (Mika et al., 2011, 2016). Amid severe labor shortages and rising wage costs, mechanical contour pruning (mechanical hedging) has emerged as an efficient technological alternative, enabling labor reductions of 50 % to 70 % compared to exclusive hand pruning (Buelow et al., 2022; Kim et al., 2024).

Previous research regarding the effects of mechanical pruning on tree fruit species shows that this method maintains or can even temporarily boost overall per-hectare yield (Lugaresi et al., 2024; Kim et al., 2024). Nevertheless, numerous authors report a moderate reduction in average fruit mass and a decline in color coverage or quality parameters, mainly caused by dense canopy foliage and restricted solar light penetration (Balan, 2015; Mika et al., 2016; Kim et al., 2024). Furthermore, tree response to contour pruning varies significantly depending on the cultivar: cultivars bearing fruit primarily on short spurs react differently than those fruiting on long shoots, exhibiting clear differences in vigor, natural crop-load regulation capacity, and leaf area recovery (Ferree & Rhodus, 1993; Buelow et al., 2022).

Although the effects of mechanical pruning have been extensively studied in young super-intensive orchards or on semi-vigorous rootstocks, it remains insufficiently clarified how mechanical contour pruning influences the balance between yield and fruit quality in aging orchards (in their post-optimal economic phase) established on dwarfing M9 rootstocks, whose fruits are intended exclusively for industrial processing (juice and concentrate production). On this low-vigorous rootstock, the interaction between mechanical hedging, the vegetative response of cultivars, and quality indicators specific to the processing industry (e.g., fruit weight, soluble solids content, yield) has not been comparatively evaluated under local pedoclimatic conditions.

Addressing these uncertainties, the objective of this study was to evaluate the effect of mechanical contour pruning on labor consumption, yield, and fruit quality parameters in various apple cultivars grown on M9 rootstock in post-optimal orchards.

The hypothesis of this study is that mechanical contour pruning significantly reduces labor time and operational costs without negatively affecting per-hectare yield and the main physicochemical parameters of fruit destined for processing (such as average fruit mass, flesh firmness, and soluble solids content), with morphophysiological responses being governed by cultivar genotype.

MATERIAL AND METHODS

Site Location and Orchard Characteristics. Research was conducted in 2026 at the "Ghermeș Agroservice" S.A. agricultural enterprise, located in southeastern Republic of Moldova. The orchard was established in 2005 on flat terrain with a gentle 1–2° slope toward the northeast on typical chernozem soil. The biological material was represented by apple cultivars (*Malus domestica* Borkh.) 'Champion', 'Golden Delicious', 'Golden Rezistent', and 'Pinova', grafted on dwarfing M9 rootstock. Planting distance was 4.0 x 1.2 m, providing a density of 2,083 trees/ha. Trees were trained as modified palmette with reduced volume, positioned in an advanced stage of bearing at the time of study.

Experimental Design. The trial was organized according to a two-factor factorial design arranged in randomized complete blocks with 4 replications; each elementary plot comprised 8 trees (total of 32 trees per variant/cultivar).

Factor A (Pruning Method):

V1 (Control): Manual maintenance and fruiting pruning, applied annually following traditional practices.

V2 (Mechanical Pruning): Mechanical contour pruning, performed annually in spring on both sides of the canopy.

Factor B (Cultivar): 'Champion', 'Golden Delicious', 'Golden Rezistent', 'Pinova'.

Pruning Execution. Mechanical contour pruning (V2) was performed in spring prior to bud swell using successive passes along both row sides. The first pass was made at an inclination angle of 12–13° relative to the vertical plane (matching natural canopy slope), while the second pass was made at an angle of 4–5° toward the tree top to prevent crowding in the upper canopy. Pruning at the base was executed 70–80 cm from the central axis, keeping the base width of the fruiting wall at 150–180 cm and reducing tree height to 3.0 m and width to 2.0 m. Corrective hand pruning in V1 targeted the stub-cutting of aged branches near the central axis to stimulate renewal shoots.

Orchard Management and Soil Analysis. Soil management, irrigation, fertilization, and phytosanitary protection were applied uniformly across the experimental field according to standard agrotechnical recommendations (Babuc, 2012). Flower thinning was accomplished via foliar urea applications (Balan & Vămășescu, 2018).

Soil core sampling was carried out in spring 2026 across 5 depth intervals (0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm) using a soil auger. Laboratory testing included: humus content (modified Tyurin method), aqueous pH (potentiometric, 1:2.5 ratio), soil texture and physical clay (pipette method), total nitrogen and total organic carbon (C_{tot}) via dry combustion on an elemental analyzer (ECS 8020), and plant-available forms of phosphorus (P_2O_5) and potassium (K_2O) by spectrophotometry and flame photometry (Machigin method).

Determination of Yield and Fruit Weight. Harvesting was carried out individually per tree at commercial consumption maturity. Per-tree yield was determined by weighing the total fruit mass harvested from all 32 trees per treatment variant, subsequently recalculated as total area yield (t/ha). Average fruit mass (g) was determined by weighing a representative sample of 5.0–6.0 kg of apples per replicate using a precision digital balance (±0.01 g, Model AS 82/220.X2) and dividing the total mass by the count of fruits in the sample.

Statistical Analysis. Data obtained were analyzed using two-way analysis of variance (two-way ANOVA) to determine the main effects of factors and their interaction (A x B). Means were separated using Tukey's test and the least significant difference ($LSD_{0.05}$) at a significance level of $p \leq 0.05$ (Dospekhov, 1985). Results are presented as mean ± standard deviation (SD). Statistical computing was executed using Microsoft Excel 2016 and STATISTICA 12.0 software packages.

RESULTS AND DISCUSSIONS

Agrochemical characteristics of soil and nutrient status. Pedological analysis (Table 1) indicates that the typical chernozem soil at the experimental site has a medium loam texture, with physical clay content ranging from 34.20 % to 36.69 % (Ursu, 2011). Soil solution reaction (aqueous pH) ranges from neutral in the topsoil

(6.79) to slightly alkaline (7.85) and alkaline at lower depths (9.31). Humus content in the plow layer (0–40 cm) is moderate (2.16–2.55 %), dropping sharply below 60 cm depth (<1.48 %). Supply of total nitrogen and nitrate nitrogen (NO_3^-) is moderate in the upper 40 cm (10.6–12.8 mg/100 g soil) and low in the subsoil. Plant-available phosphorus (P_2O_5) and exchangeable potassium (K_2O) are low to moderate (2.87–3.14 mg/100 g soil P_2O_5 and 15.3–18.5 mg/100 g soil K_2O, respectively).

Based on these agrochemical traits, active nutrient requirements were calculated to maintain a yield potential of 40.0–50.0 t/ha: 180–225 kg/ha N, 100–125 kg/ha P_2O_5 și 120–150 kg/ha K_2O (Babuc, 2012).

Table 1

Physicochemical characteristics of typical chernozem soil in the experimental orchard

Sample Depth (cm)	Humus (%)	Aqueous pH	Physical Clay (%)	Total Carbon (%)	Nutrients Content (mg/100 g soil)		
					NO_3	P_2O_5	K_2O
0–20	2.55	6.79	34.20	2.06	12.8	3.14	18.5
20–40	2.16	7.85	34.38	1.82	10.6	2.87	15.3
40–60	1.89	9.31	34.51	1.68	7.2	2.31	11.8
60–80	1.48	9.27	35.67	1.43	4.8	1.67	7.5
80–100	0.87	—	36.69	1.03	2.7	1.19	3.7

Influence of Pruning Method and Cultivar on Fruit Yield. Harvest evaluation in 2026 demonstrates that switching from manual pruning to mechanical contour pruning does not cause yield reductions in apple trees on M9 rootstock (Table 2).

Table 2

Influence of pruning method and cultivar on fruit yield (kg/tree)
(S.A. "Ghermeș Agroservice", M9 rootstock, spacing 4.0 x 1.2 m, year 2026, n = 4 replications)

Factor A (Pruning) / Factor B (Cultivar)	'Champion'	'Golden Delicious'	'Golden Rezistent'	'Pinova'	Factor A Mean
V1 (Control - Manual)	27.93 ±1.84	21.25 ±1.52	19.95 ±1.10	17.73 ±1.05	21.71 ±4.02
V2 (Mechanical)	26.98 ±1.76	24.05 ±1.68	19.83 ±1.25	17.98 ±1.12	22.21 ±3.78
Factor B Mean	27.45 ±1.72a	22.65 ±2.05b	19.89 ±1.11c	17.85 ±1.02c	21.96 *(Overall Mean)*

ANOVA Note:
Factor A (Pruning): df = 1, F_{calc} = 0.38, p = 0.542 (non-significant);
Factor B (Cultivar): df = 3, F_{cal} = 10.30, p < 0.001 (statistically significant);
Interaction A B: df = 3, F_{calc} = 0.39, p = 0.761 (non-significant).

Different letters across the Factor B mean row indicate statistically significant differences according to Tukey's test (p ≤0.05). ; $LSD_{0.05}$ Factor A = 2.69 kg/pom; ; $LSD_{0.05}$ Factor B = 3.81 kg/pom; ; $LSD_{0.05}$ Interacțiune = 5.38 kg/pom.

Data analysis confirms that there is no statistically significant difference between manual pruning (21.71 kg/tree, equivalent to 45.2 t/ha) and mechanical pruning (22.21 kg/tree, equivalent to 46.2 t/ha) (F_{calc} = 0.38, F_{crit} = 4.26, p = 0.542). The slight increase of 0.50 kg/tree recorded in V2 falls within the experimental error margin ($LSD_{0.05}$ = 2.69 kg/tree). Thus, mechanical pruning preserves active vegetative surface area and bearing potential without disrupting physiological balance.

In contrast to pruning method, the genotypic factor (Cultivar) exerted a dominant and highly significant effect (F_{calc} = 10.30 > F_{crit} = 3.07, p < 0.001). The cultivar 'Champion' was the most productive (27.45 kg/tree), significantly outperforming 'Golden Delicious' (22.65 kg/tree), 'Golden Rezistent' (19.89 kg/tree), and 'Pinova' (17.85 kg/tree). Since the interaction A x B was non-significant (F_{calc} = 0.3, p = 0.761), it is confirmed that all cultivars maintain their yield hierarchy regardless of whether pruning is performed manually or mechanically.

Influence of Pruning Method and Cultivar on Average Fruit Weight. Gravimetric parameters of fruit reacted differently to the studied factors, showing significant variations in fruit size grade (Table 3).

Table 3

Influence of pruning method and cultivar on average fruit weight (g/fruit)
(S.A. "Ghermeș Agroservice", M9 rootstock, spacing 4.0 x1.2 m, year 2026, n = 4 replications)

Factor A (Pruning) / Factor B (Cultivar)	**'Champion'**	**'Golden Delicious'**	**'Golden Rezistent'**	**'Pinova'**	**Factor A Mean**
V1 (Control - Manual)	122.10 ±4.12	112.50 ±3.85	109.15 ±3.20	96.75 ±2.90	110.13 ±9.88a
V2 (Mechanical)	107.85 ±3.90	95.98 ±3.10	105.10 ±3.45	95.20 ±2.80	101.03 ±6.12b
Factor B Mean	114.98 ±8.20a	104.24 ±9.15b	107.13 ±3.60ab	95.98 ±2.20c	105.58 *(Overall Mean)*

ANOVA Note:
Factor A (Pruning): df = 1, F_{calc} = 5.12, p = 0.038 (statistically significant);
Factor B (Cultivar): df = 3, F_{cal} = 8.45, p < 0.001 (statistically significant);
Interaction A x B: df = 3, F_{calc} = 0.54, p = 0.659 (non-significant).
Different letters along the Factor A mean column and Factor B mean row indicate statistically significant differences (p ≤0.05).; $LSD_{0.05}$ F_{actor} A = 6.48 g; $LSD_{0.05}$ F_{actor} B = 9.17 g; $LSD_{0.05}$ Interaction = 12.96 g.

Analysis of variance for average fruit weight indicates a statistically significant effect of Factor A (Pruning) (F_{calc} = 5.12 > F_{crit} = 4.26, p = 0.038). The application of mechanical contour pruning (V2) reduced average fruit mass from 110.13 g to 101.03 g, yielding a decrease of 9.10 g/fruit, which exceeds the threshold of $LSD_{0.05}$ = 6.48 g.

This size reduction represents a normal physiological response: non-selective mechanical hedging removes peripheral branches, stimulating bud

development on interior short spurs. The higher number of set fruits per tree intensifies competition for photo assimilates, leading to lower individual fruit weight (Mika et al., 2016). However, for fruit intended for industrial processing (juices, concentrates), this adjustment in fruit size is fully acceptable technologically, as it is compensated by the maintenance of total harvested mass per hectare.

The genotypic factor (Cultivar) also significantly influenced fruit weight (F_{calc} = 8.45, p = 0.001). Cultivar 'Champion' produced the largest fruit size (114.98 g), followed by 'Golden Rezistent' (107.13 g and 'Golden Delicious' (104.24 g), whereas 'Pinova' recorded the lowest average fruit mass (95.98 g). The interaction A x B was non-significant (F_{calc} = 0.54, p = 0.659), demonstrating that fruit size reduction resulting from mechanical pruning follows a uniform pattern across all tested cultivars.

CONCLUSIONS

1. Under the experimental conditions of 2026, mechanical contour pruning (V2) applied to both canopy sides did not produce statistically significant differences in fruit yield compared to traditional manual pruning (V1), recording 22.21 kg/tree in V2 versus 21.71 kg/tree in V1 ($LSD_{0.05}$ = 2.69 kg/tree).
2. The genotypic factor (cultivar) significantly influenced productivity levels, with cultivar 'Champion' attaining the highest average yield (27.45 kg/tree), while 'Pinova' registered the lowest bearing level (17.85 kg/tree). The interaction between pruning method and cultivar was statistically non-significant ($F_{calc} = 0.39 < F_{0.05}$).
3. Mechanical contour pruning resulted in a statistically proven reduction in average fruit weight from 110.13 g (V1) to 101.03 g (V2) ($p < 0.05$), a phenomenon caused by heightened competition for photo assimilates inside the canopy. However, this reduction in fruit size does not diminish the commercial value of apples intended for industrial processing.

ACKNOWLEDGMENT

This study was supported by the Technical University of Moldova through the institutional subprogram "Research and Extension Center for Agriculture, Biodiversity and Rural Development" No. 020499

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