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Evaluation of the vegetative performance of perspective apple cultivars, grafted on Geneva®, Budagovsky and Malling rootstocks

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SUMMARY

This study aimed to evaluate the effects of nine apple rootstocks on the vegetative growth and formation of fruit-bearing structures in 'Najdared' and 'Fuji San 51' cultivars in an intensive orchard. The examined rootstocks included clones of the Geneva® series (G.11, G.16, G.41, G.214), clones of Budagovsky series (B.9, B.10), and M.9-derived clones (T337, RN29, FL56). Measured parameters were tree height, trunk cross-sectional area (TCSA), density and length of fruit bearing parts. The obtained results clearly indicated that rootstock choice significantly affected the vegetative vigor, trunk development, and the density of fruit bearing parts in both cultivars. Cultivars 'Najdared' and 'Fuji San 51' exhibited pronounced vegetative growth on G.214 and M.9 RN29 rootstocks, as reflected in both tree height increment and trunk diameter thickening. All combinations showed a dominance of generative growth according to the ratio of short and long fruiting shoots for both cultivars in 2022, except for trees grafted on G.11 rootstocks. These findings emphasize that appropriate rootstock selection is a critical factor for optimizing vegetative growth and yield potential in intensive apple production.

Keywords: *apple; rootstocks; cultivars; adaptability*

INTRODUCTION

The international market share of apples has been steadily increasing in recent years, leading to intensified competition in apple production. Nowadays, profitable apple production requires intensive cultivation technologies and the use of highly productive dwarf rootstocks (Russo et al., 2007; Csihon, 2014). Establishing new orchards requires a comprehensive management strategy, which encompasses the selection of rootstock and cultivar, training system, tree density, fruit quality, yield, and optimization of marketable value (Goedegebure, 1993; Sansavini & Musacchi, 2002; Robinson et al., 2007; Dremák et al., 2016; Lordan et al., 2019; Csihon et al., 2022). The adoption of dwarf rootstocks has been a key factor in increasing planting density, achieving earlier bearing, and accelerating the return on investment. Furthermore, rootstocks play a critical role in the allocation of resources between vegetative and generative growth processes (Robinson, 2011). Root development determines the efficiency of nutrient and water uptake, the ultimate size of the tree, and indirectly affects the frequency and severity of phytopathological risks. Modern rootstocks are now available with specific resistance or tolerance to the most common pathogens, such as fire blight (*Erwinia amylovora*), Phytophthora crown and root rot (*Phytophthora cactorum*), and apple replant disease (ARD) (Claffey & Farcuh, 2022). Worldwide, the M.9 rootstock has been the most widely adopted (Piestrzeniewicz et al., 2018). However, its limitations include susceptibility to winter frost, vulnerability to fire blight and Phytophthora, and a predisposition for burr knots and suckers. Trees grafted on M.9 rootstock reach the first harvest within 1–2 years after planting and achieve significant yields by the third to fourth year, but after 10–15 years, both yield quantity and quality decline (Csigai et al., 2005; Webster et al., 2007). M.9 rootstocks are also sensitive to replant problems, and graft union stability is limited (Robinson, 2011). Breeding programs have targeted the mitigation of these limitations and the potential replacement of M.9 rootstocks. Furthermore, breeding efforts prioritize tolerance to abiotic stresses, as the use of stress-tolerant rootstocks represents one of the most sustainable strategies for their mitigation (Tworkoski et al., 2016; Li et al., 2024; Martínez et al., 2024).

The Geneva® series, bred by Cornell University and the USDA, includes clones such as G.11, G.16, G.41, and G.214. These clones typically provide high yields and exhibit resistance to fire blight, Phytophthora and ARD (Claffey & Farcuh, 2022). Additional advantages of these clones include ease nursery propagation and tolerance to extreme temperatures, which is particularly important in the context of global climate change (Cosmulescu, 2026).

The Budagovsky rootstock series originates from Michurinsk, Russia, includes clones such as B.9, B.10, and B.118. These rootstocks are characterized by adaptation to cold climates and in some clones, resistance to powdery mildew and Phytophthora. In recent years, the B.9 rootstock has gained popularity due to its resistance to bacterial fire blight (Robinson, 2011). These rootstocks are particularly suitable for colder regions where critically low winter temperatures are frequent.

Therefore, the correct selection of rootstock is not only a botanical issue, but a strategic decision in modern apple production (Cornille et al., 2019; Reig et al., 2020; Xu et al., 2021). No universal rootstock exists, as environmental factors significantly influence their productivity and effects on the scion; certain traits may emerge in specific rootstock–cultivar combinations that were previously hidden (Fazio & Robinson, 2024). Consequently, it is critical to evaluate

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each combination under local growing conditions before orchard-scale implementation.

Limited information is available on the effects of modern rootstocks on the vegetative growth of the newest apple cultivars. The aim of this study was to evaluate tree height, trunk cross-sectional area, and the number and length of branches during the early growth stage of trees in the case of 'Najdared' and 'Fuji San 51' cultivars, under intensive orchard management. The results of the study can provide useful information regarding the vegetative performance of the non-bearing stage, which can help the application of cultivar specific production technology in the years after the planting.

MATERIALS AND METHODS

Description of the experiment area

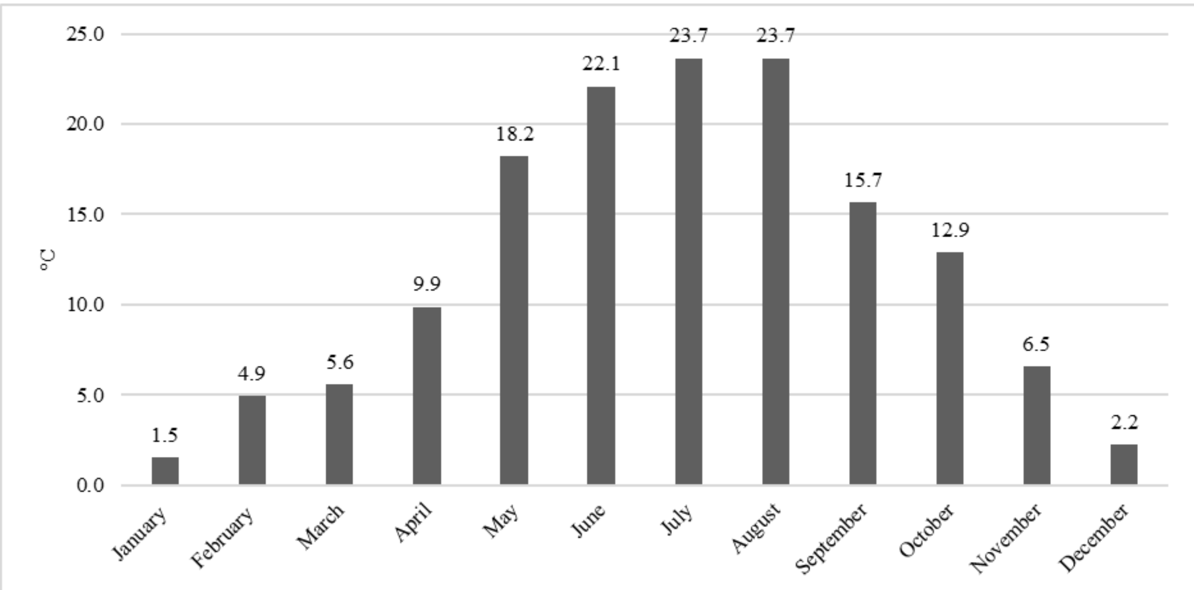
The study was conducted in Central Hungary, close to the city of Ráckeve, in the intensive apple orchard of Almatech Ltd. during the 2021–2022 seasons. The orchard was equipped with drip irrigation system and anti-hail net. Trees were planted in the autumn of 2021 using Knipp-trees, which were spaced at 3.5 m × 0.8 m for 'Fuji San 51' and 3.5 m x 0.6 m for 'Najdared'. Trees were trained to super spindle canopy. The experimental site is characterized by meadow alluvial soil with a medium humus content of approximately 2.83% in the 0–30 cm soil layer, whereas at a depth of 30–60 cm this value was 1.19%. The "Arany" soil heaviness index is 37–43 depending on the soil layer (*Table 1*).

Table 1. **Soil parameters of the orchard (Ráckeve, 2021)**

Soil layer	0–30 cm	30–60 cm
pH-H_2O	7.26	7.57
"Arany" soil heaviness index	43	39
$CaCO_3$ (%)	19.2	41.8
Total soluble salts (%)	<0.020	<0.020
Humus (%)	2.83	1.19
P_2O_5 (mg kg^{-1})	339	142
K_2O (mg kg^{-1})	394	197
Mg (mg kg^{-1})	333	248
Zn (mg kg^{-1})	4.12	1.6

The main meteorological parameters are presented in *Figure 1–3*. Monthly mean temperature ranged from 1.5 to 23.7 °C in the year of 2022 as shown in *Figure 1*. Significant frost events did not occur during the study period; the lowest temperature recorded was −1.9 °C in January 2022 (*Figure 2*). The annual average precipitation in Hungary is 550–700 mm. During the growing season, apple trees generally require around 750–800 mm of precipitation (Nyéki & Soltész, 2011), whereas the region received only 474 mm in 2022 (*Figure 3*).

Figure 1. **Monthly mean temperatures in the experimental orchard (Ráckeve, 2022)**



Source of data: https://meteostat.net/en/place/hu/rackeve?s=12846&t=2022-01-01/2022-12-31

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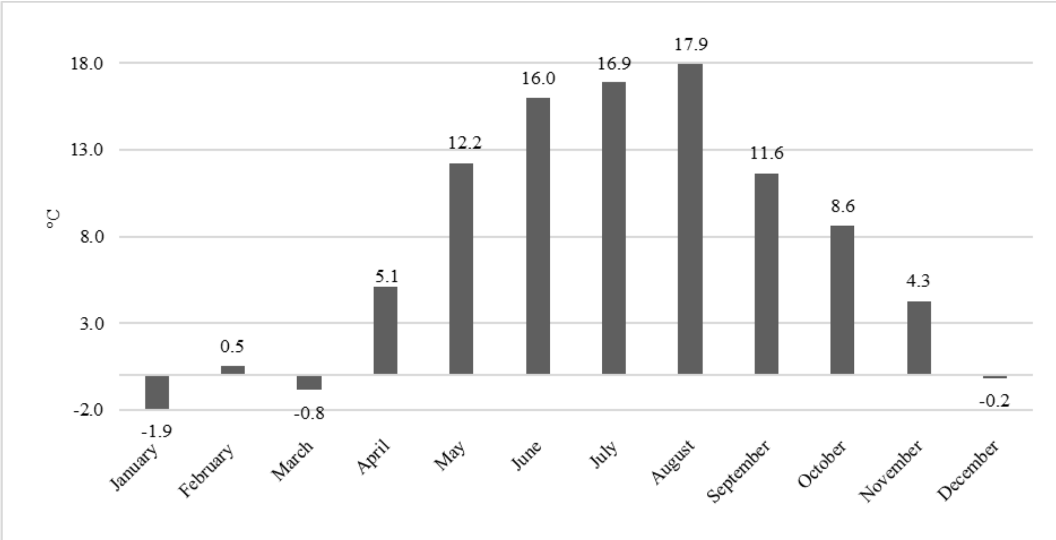
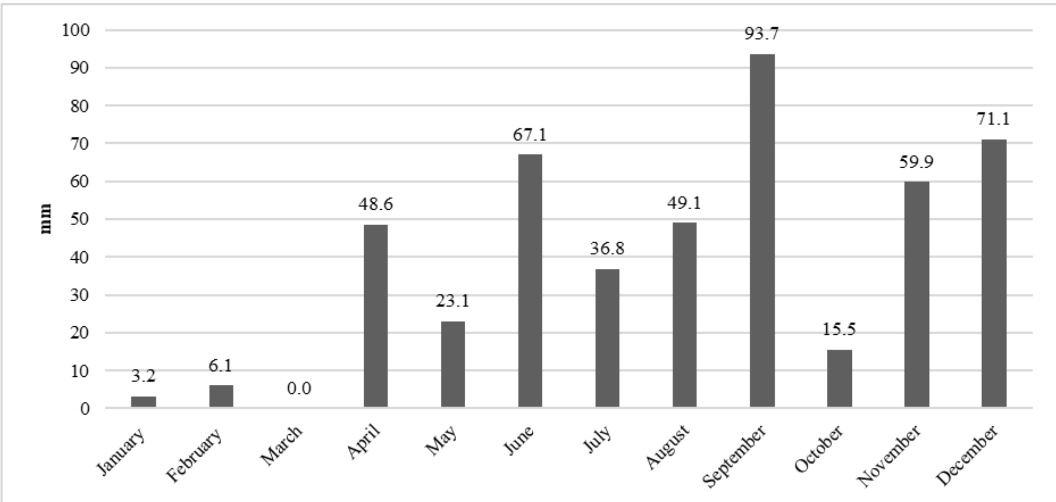
Figure 2. **Monthly minimum temperatures in the experimental orchard (Ráckeve, 2022)**



Source of data: https://meteostat.net/en/place/hu/rackeve?s=12846&t=2022-01-01/2022-12-31

Figure 3. **Monthly precipitation in the experimental orchard (Ráckeve, 2022)**



Source of data: https://meteostat.net/en/place/hu/rackeve?s=12846&t=2022-01-01/2022-12-31

Examined rootstocks and cultivars

'Najdared' is a Polish-bred apple cultivar, developed as a more intensely colored mutation of 'Idared'. Fruit size is medium to large, depending on crop load, and the fruits are globular in shape with excellent coloration. The flesh is white, crisp, and juicy. Some reports suggest that its flavor surpasses that of 'Idared' (Klimek, 2016). The harvest period varies between October 10 and 20, depending on the growing season, and postharvest storability is good, ranging from 3 to 9 months under modern storage technologies (Rutkowski & Kruczyńska, 2009). During the first years after planting, trees exhibit vigorous growth, producing numerous short shoots and a dense canopy, with slightly spreading branches (Klimek, 2014). The cultivar shows moderate susceptibility to powdery mildew and fire blight.

'Fuji San 51' is the result of Italian breeding, officially registered as SAN CIV® FUCIV51pbr. It is a clone of the classic 'Fuji' characterized by more uniform and intense fruit coloration (Nari et al., 2020). The fruits are large, with high sugar content and a well-balanced sugar–acid ratio. The cultivar is less sensitive to sunburn than other 'Fuji' clones, but it may exhibit biennial bearing (FruitToday, 2019). In the breeding location, fruit harvesting begins in late autumn.

In this research, nine promising apple rootstocks were evaluated: clones of Geneva series (G.11, G.16, G.41, and G.214), clones of the Budagovsky (B.9 and B.10), and M.9-derived clones (T337, RN29, and FL56). Throughout the experiment, several vegetative traits were measured, including trunk cross-sectional area (cm^2), tree height (cm), density (number/cm^2) and length of fruit-bearing parts (cm).

Trunk diameter of the trees was measured at a point halfway between the graft union and the lowest branching point using a digital caliper, each year, after leaf fall. Trunk cross-sectional area (TCSA) was

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calculated from the measured diameter, and growth parameters were subsequently standardized with respect to this variable. Tree height was measured as the distance between the ground and the tree top. Number and length of fruiting shoots were assessed in the entire trees, during leaf fall and bud sprouting in both years. Later these parameters were calculated to trunk cross-sectional area. Shoot length and tree height were determined using tape measure. The fruiting shoots on each tree were categorized by length into short (1–5 cm), medium (6–20 cm), and long (>20 cm) classes. For each rootstock, five replications were included to assess the vegetative performance of young apple trees. The following abbreviations will be used throughout the manuscript: TCSA (trunk cross sectional area), TH (tree height), SFP (short fruiting parts), MFP (medium fruiting parts), LFP (long fruiting parts), and TNGP (total number of growth points).

Data analyses

The measurement data were evaluated using analysis of variance (ANOVA) performed with an Excel macro program developed by László Tolner (Aydinalp et al., 2010), based on the algorithm described by Sváb (1981). Relationships among the measured parameters were analysed using Pearson correlation coefficients (r) and their associated significance levels (p = 0.05) in Microsoft Excel with the Analysis ToolPak add-in.

RESULTS AND DISCUSSION

Tree height

The expected tree height of knipp trees at planting is 160–180 cm (Gonda & Fülep, 2011). In the case of ‘Fuji San 51’, height of the planted trees ranged between 164 and 192 cm in 2021 (*Table 2*) thus, the trees reached the expected height before planting. The lowest values were recorded for trees grafted onto M.9 FL56 (164 cm) and B.9 (165 cm) rootstocks, whereas trees grafted onto G.214 showed the most vigorous growth during the nursery phase (192 cm).

Table 2. **Tree height (cm) of ’Fuji San 51’ and ’Najdared’ cultivars in 2021–2022**

	'Fuji San 51'		'Najdared'	
	2021	**2022**	**2021**	**2022**
G.11	182^{ab}	232^{a}	155^{a}	233^{ab}
G.16	181^{ab}	234^{a}	167^{b}	222^{a}
G.41	178^{ab}	219^{a}	168^{b}	229^{ab}
G.214	192^{b}	246^{ab}	169^{b}	260^{c}
B.9	165^{a}	216^{a}	153^{a}	214^{a}
B.10	179^{ab}	224^{a}	170^{b}	235^{b}
M.9 FL56	164^{a}	222^{a}	165^{ab}	220^{a}
M.9 T337	173^{a}	233^{a}	168^{b}	231^{ab}
M.9 RN29	177^{ab}	228^{a}	162^{ab}	226^{ab}
$LSD_{0.05}$	10	18	6	10

Values followed by the same letter are not significantly different according to LSD test (p=0.05).

In the case of cultivar ‘Najdared’ height of the planted trees ranged from 153 cm (B.9) to 170 cm (B.10) in 2021, indicating uniform planting material (*Table 2*). Trees grafted onto G.11 and B.9 rootstocks exhibited significantly lower values compared to the other combinations (153–155 cm). In the following year, the strong growth habit of G.214 rootstock was also pronounced on cultivar ‘Najdared’, as trees increased in height by 91 cm during the first growing season. In 2022, tree height values varied between 214 cm (B.9) and 260 cm (G.214). Regardless of cultivar, trees on B.9 showed weaker vegetative growth, while G.214 was characterized by greater vigor.

Trunk cross-sectional area

As a reliable measure of overall tree growth, trunk cross-sectional area (TCSA) captures the specific interactions between cultivars and rootstocks (Čmelik et al., 1998). In the case of ‘Fuji San 51’, TCSA was the lowest for M.9 FL56 (1.29 cm²), B.9 (1.30 cm²), and M.9 T337 (1.31 cm²) rootstocks, whereas trees grafted onto G.16 rootstock exhibited the highest trunk thickness values (1.80 cm²) at the time of planting, in 2021 (*Table 3*), however no statistically significant differences were observed among the combinations. Based on the data obtained in 2022, it can be concluded that the M.9 RN29 rootstock demonstrated the highest thickening rate, with an increase of 1.98 cm² in trunk cross-sectional area during the first growing season, while trees grafted onto G.214 showed only a moderate increase of 0.97 cm². In contrast to tree height, no substantial differences were detected among cultivars in the changes of trunk cross-sectional area. In 2022, the lowest TCSA was recorded in trees grafted onto B.9 (2.42 cm²), whereas the largest trunk cross-sectional area values were observed in trees grafted onto M.9 RN29 (3.61 cm²). These combinations differed by 1.19 cm² in TCSA.

For ‘Najdared’, the lowest TCSA value was recorded for the G.214 rootstock (0.87 cm²) in 2021, whereas the highest values were recorded for trees grafted onto G.16 (1.39 cm²) (*Table 3*). In 2022, TCSA values ranged from 2.53 cm² (B.9) to 3.65 cm² (B.10), but no statistically significant differences were observed among the combinations. The most vigorous thickening was demonstrated by trees grafted onto M.9 RN29, with an increase of 2.35 cm² in trunk cross-sectional area during the first growing season in the orchard. A similar trend was noted for the B.10 combination, which showed an increase of 2.28 cm². In contrast, the slowest thickening was recorded in trees grafted onto G.11, where the increment amounted to only 1.43 cm². A similar trend was observed across cultivars, with M.9 RN29 exhibiting the most intensive trunk thickening in both ‘Fuji San 51’ and ‘Najdared’. However, based on the data from the two-year period, no statistically significant differences were observed among the combinations.

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Table 3. **Trunk cross sectional area (cm^2) of 'Fuji San 51' and 'Najdared' cultivars in 2021–2022**

	'Fuji San 51'		'Najdared'	
	2021	**2022**	**2021**	**2022**
G.11	1.53^{a}	3.05^{ab}	1.16^{ab}	2.59^{a}
G.16	1.80^{ab}	3.30^{ab}	1.39^{b}	3.13^{ab}
G.41	1.63^{ab}	2.91^{a}	1.27^{ab}	3.11^{a}
G.214	1.47^{a}	2.44^{a}	0.87^{a}	2.90^{a}
B.9	1.30^{a}	2.42^{a}	1.06^{a}	2.53^{a}
B.10	1.56^{a}	2.68^{a}	1.37^{ab}	3.65^{ab}
M.9 FL56	1.29^{a}	2.66^{a}	1.26^{ab}	3.02^{a}
M.9 T337	1.31^{a}	2.87^{a}	1.22^{ab}	3.14^{ab}
M.9 RN29	1.63^{ab}	3.61^{ab}	1.27^{ab}	3.62^{ab}
LSD$_{0.05}$	0.28	0.60	0.25	0.59

Values followed by the same letter are not significantly different according to LSD test (p=0.05).

Number of fruiting shoots

Density of the fruit bearing parts of the examined cultivars can be seen in *Table 4–5*. In the case of 'Fuji San 51', the number of short fruiting parts (<5 cm) ranged from 1.2 to 5.3 per cm² in 2021 (*Table 4*). The lowest values were recorded for trees grafted onto G.16, while the highest occurred on M.9 FL56 rootstock. The G.11, G.16, and B.10 rootstocks exhibited a higher proportion (3.2–4.2 per cm^2) of long fruiting shoots (>20 cm) compared to short ones, whereas in all other rootstocks, the number of short shoots was dominant. A positive correlation was observed between trunk cross-sectional area (TCSA) and the number of long shoots (r=0.59), as shown in *Table 7*. At the end of the following vegetation period (2022), we observed a high number of long shoots in the case of G.11 (3.3 per cm^2), while the number of short parts was considerably lower than other rootstocks. Significantly higher short shoot number were observed for the G.16 and G.214 rootstocks compared to the other rootstocks.

Table 4. **Number of fruit bearing parts (number/cm^2) of 'Fuji San 51' cultivar in 2021–2022. (Short: 1–5 cm, medium: 6–19 cm, long: >20 cm)**

	'Fuji San 51'					
	2021			2022		
	Short	**Medium**	**Long**	**Short**	**Medium**	**Long**
G.11	2.0^{a}	2.2^{a}	3.2^{a}	3.6^{a}	0.8^{a}	3.3^{ab}
G.16	1.2^{a}	0.8^{a}	4.1^{ab}	9.1^{b}	0.9^{a}	2.3^{a}
G.41	3.4^{ab}	1.1^{a}	2.6^{a}	4.9^{a}	1.5^{ab}	2.3^{a}
G.214	4.4^{ab}	1.5^{a}	3.4^{a}	8.7^{b}	0.7^{a}	3.0^{ab}
B.9	4.4^{ab}	1.1^{a}	3.1^{a}	8.1^{ab}	1.2^{a}	1.9^{a}
B.10	2.1^{a}	1.1^{a}	4.2^{ab}	7.8^{ab}	2.3^{b}	1.9^{a}
M.9 FL56	5.3^{b}	1.4^{a}	3.0^{a}	6.3^{ab}	0.5^{a}	2.5^{a}
M.9 T337	3.8^{ab}	2.7^{ab}	2.3^{a}	6.0^{ab}	0.5^{a}	3.1^{ab}
M.9 RN29	3.9^{ab}	1.7^{a}	2.7^{a}	5.9^{ab}	1.3^{a}	2.4^{a}
LSD$_{0.05}$	1.7	1.3	1.2	2.3	0.8	0.8

Values followed by the same letter are not significantly different according to LSD test (p=0.05).

In cultivar 'Najdared', trees grafted onto B.10 rootstock developed higher number of medium-length shoots (6–20 cm), while in other cases, short shoots were dominant (*Table 5*). The number of short parts varied from 4.4 to 9.4 per cm². The lowest value was observed in B.10, while the highest occurred in the G.214 rootstock. Medium-length shoots extended from 0.8 to 2.7 per cm² in 'Fuji San 51' and was between 1.4 and 6.0 per cm² in 'Najdared' cultivar. The number of long fruiting shoots was higher for 'Fuji San 51' (2.3–4.2 per cm²), and lower for 'Najdared' (0.4–3.4 per cm^2). In 2022, G.16, M.9 FL56 and M.9 T337 exhibited high number of short fruiting shoots (9.1–9.7 per cm^2) in cultivar 'Najdared', while trees grafted on G.11 and G.214 rootstock showed significant lower values. Trees grafted onto G.11 exhibited the highest number of long shoots. Positive correlations were observed between TCSA and medium-length fruiting parts (r=0.54), long fruiting parts (r=0.57) in 2021 (*Table 7*). In contrast, in 2022 these relationships were no longer statistically significant (*Table 8*).

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Table 5. **Number of fruit bearing parts (number/cm²) of 'Najdared' cultivar in 2021–2022. (Short: 1–5 cm, medium: 6–19 cm, long: >20 cm)**

	'Najdared'					
	2021			2022		
	Short	**Medium**	**Long**	**Short**	**Medium**	**Long**
G.11	6.8ᵃ	1.4ᵃ	0.4ᵃ	3.9ᵃ	1.4ᵃ	5.4ᵇ
G.16	5.9ᵃ	4ᵃᵇ	2.7ᵃᵇ	9.1ᵇ	0.8ᵃ	2.5ᵃ
G.41	6.4ᵃ	4.7ᵃᵇ	1.3ᵃ	6.5ᵃᵇ	2.0ᵃᵇ	3.0ᵃ
G.214	9.4ᵃᵇ	2.7ᵃ	0.6ᵃ	4.9ᵃ	1.0ᵃ	4.0ᵃᵇ
B.9	5.4ᵃ	2.0ᵃ	0.4ᵃ	7.7ᵃᵇ	1.5ᵃ	2.6ᵃ
B.10	4.4ᵃ	5.2ᵃᵇ	1.3ᵃ	7.7ᵃᵇ	1.9ᵃᵇ	2.9ᵃ
M.9 FL56	7.0ᵃ	3.6ᵃ	1.6ᵃᵇ	9.4ᵇ	2.6ᵃᵇ	2.3ᵃ
M.9 T337	7.0ᵃ	6.0ᵃᵇ	1.2ᵃ	9.7ᵇ	2.8ᵃᵇ	3.2ᵃ
M.9 RN29	7.3ᵃ	4.0ᵃᵇ	1.0ᵃ	6.2ᵃᵇ	2.2ᵃᵇ	3.1ᵃ
$LSD_{0.05}$	3.6	2.4	1.2	2.1	1.1	1.1

Values followed by the same letter are not significantly different according to LSD test (p=0.05).

Total number of growth points

The total number of growth points (TNGP) reflects to the branching capacity of the trees. This value was obtained by summarizing the numbers of short, medium and long fruiting shoots. In 2021, it ranged from 6.0 per cm² (G.16) to 9.6 per cm² (M.9 FL56) for 'Fuji San 51', and from 7.8 per cm² (B.9) to 14.1 per cm² (M.9 T337) for 'Najdared' (*Table 6*). With the exception of the B.9 rootstock, all trees exhibited higher total numbers of growth points in 'Najdared' than in 'Fuji San 51' in 2021.

Table 6. **Total number of growth points (number/cm²) of 'Fuji San 51' and 'Najdared' cultivars in 2021–2022**

	'Fuji San 51'		'Najdared'	
	2021	**2022**	**2021**	**2022**
G.11	7.4ᵃ	7.7ᵃ	8.7ᵃ	10.7ᵃ
G.16	6.0ᵃ	12.3ᵇ	12.6ᵃᵇ	12.4ᵃᵇ
G.41	7.1ᵃ	8.7ᵃ	12.4ᵃᵇ	11.4ᵃ
G.214	9.3ᵃᵇ	12.3ᵇ	12.7ᵃᵇ	10.0ᵃ
B.9	8.5ᵃᵇ	11.3ᵃᵇ	7.8ᵃ	11.8ᵃ
B.10	7.4ᵃ	12.0ᵃᵇ	11.0ᵃᵇ	12.5ᵃᵇ
M.9 FL56	9.6ᵃᵇ	9.2ᵃ	12.2ᵃᵇ	14.3ᵇ
M.9 T337	8.8ᵃᵇ	9.6ᵃ	14.1ᵇ	15.7ᵇ
M.9 RN29	8.3ᵃᵇ	9.6ᵃ	12.3ᵃᵇ	11.5ᵃ
$LSD_{0.05}$	2.1	2.2	3.0	2.0

Values followed by the same letter are not significantly different according to LSD test (p=0.05).

In 2022, regarding the number of growth points, the highest branching density in 'Fuji San 51' was observed on trees grafted onto G.16 and G.214 rootstocks (12.3–12.3 per cm²), whereas in 'Najdared', trees grafted onto M.9 FL56 and M.9 T337 rootstocks were outstanding (14.3-15.7 per cm²).

Lower TNGP values were recorded for 'Najdared' on G.11 and G.214 rootstocks, and for 'Fuji San 51' on G.11 and G.41 rootstocks. In cultivar 'Najdared', weaker vegetative growth (tree height and TCSA) was associated with a lower number of growth points in both 2021 and 2022 (*Table 2–3*), which may be explained by the higher soil sensitivity of B.9. However, a similarly low number of growth points was recorded in the more vigorous G.214, despite its greater tree height.

In both years (2021–2022), a statistically significant positive correlation (*r*=0.56–0.56) was found between TNGP and TCSA in 'Najdared' (*Tables 7–8*).

This study investigated the effect of Geneva, Budagovsky, and Malling 9 rootstocks on the vegetative development of two apple cultivars. Statistically significant differences were observed among rootstocks within both 'Fuji San 51' and 'Najdared' apple cultivars regarding the parameters examined (*Tables 2, 3, 4, 5* and *6*).

Table 7. **Pearson correlation coefficients (*r*) of four pairs of measured parameters for the 'Fuji San 51' and 'Najdared' cultivars (Ráckeve, Hungary, 2021)**

Cultivar/ correlation pairs	TCSA *vs* SFP	TCSA *vs* MFP	TCSA *vs* LFP	TCSA *vs* TNGP	TH *vs* TCSA
'Fuji San 51'	0.34	0.04	**0.59**	0.00	0.34
'Najdared'	0.01	**0.54**	**0.57**	**0.56**	0.07

TCSA: trunk cross sectional area, SFP: short fruiting part, MFP: medium fruiting part, LFP: long fruiting part, TNGP: total number of growth points, TH: tree height. Significant (*p*=0.05) relationships are indicated as bold.

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Table 8. **Pearson correlation coefficients (*r*) of four pairs of measured parameters for 'Fuji San 51' and 'Najdared' cultivars (Ráckeve, Hungary, 2022)**

Cultivar/ correlation pairs	TCSA *vs* SFP	TCSA *vs* MFP	TCSA *vs* LFP	TCSA *vs* TNGP	TH *vs* TCSA
'Fuji San 51'	0.05	0.08	0.43	0.26	0.01
'Najdared'	0.35	0.38	0.00	**0.56**	0.01

TCSA: trunk cross sectional area, SFP: short fruiting part, MFP: medium fruiting part, LFP: long fruiting part, TNGP: total number of growth points, TH: tree height. Significant (p=0.05) relationships are indicated as bold.

In the case of 'Fuji San 51', trees grafted onto the B.9 rootstock exhibited lower growth vigour in both years (tree height, TCSA). According to Gonda and Fülep (2011), after planting, during the first growing season trees produce only minimal growth, new growth appears mainly as rosettes. This can be attributed to the reduced root system of knipp trees after transplanting, resulting in an imbalance with the aboveground canopy. Meanwhile in our trial, for the most rootstock-cultivar combinations stronger growth was observed after the planting, in 2022, e.g. trees on G.214 rootstocks reached a height of approximately 2.5 m.

Robinson et al. (2011) investigated the growth and yield parameters of several rootstocks, including B.9, M.9 T337, and M.9 RN29 (Nic 29). In that study, M.9 clones were found to exhibit significantly larger trunk cross-sectional area (TCSA) compared to B.9. In our study, trees with FL56, T337, and B.9 rootstocks exhibited the smallest trunk cross-sectional values, confirming the lower vigour of B.9 rootstock. Czynczyk and Bielicki (2012) reported a positive correlation between tree height and trunk cross-sectional area (TCSA). In our study, in 2021, M.9 FL56 rootstock exhibited the lowest vigour based on both tree height and trunk cross-sectional data. A similar result was described by Nyvlt et al. (2024), who reported that trees on G.11, FL56, and Pajam 1 rootstocks exhibited the lowest TCSA values. In 2021, an inverse relationship was observed between TCSA and spur number, as FL56 trees showed a significantly higher proportion of short fruiting shoots compared to the other combinations. A similar trend was observed in 2022, where RN29 trees with higher trunk cross-sectional area exhibited a significantly lower number of growing points, indicating reduced branching capacity in more vigorous trees. In the same year, trees grafted onto G.214, which exhibited a slower trunk thickening dynamic, showed a high spur density. These results are in contrast with those reported by Choi et al. (2019), where the G.214 rootstock showed a higher rate of trunk thickening compared to M.9 T337 and G.41.

In our trial, with cultivar 'Najdared', G.214, as well as B.10 and G.16, were identified as rootstocks associated with vigorous vegetative growth. According to Dallabetta et al. (2018), 'Gala' grafted onto G.16 rootstock exhibited significantly greater growth compared to those on M.9 T337. Furthermore, their results indicate that 'Fuji' trees were also larger on Geneva rootstocks than on the M.9 T337 clone. In 2022, G.11 exhibited the slowest TCSA increase, which was associated with a low number of short bearing parts, a high number of long shoots, and overall low growth point density. Similarly, Fazio et al. (2013) reported this rootstock (G.11) to exhibit weak trunk thickening and low trunk cross-sectional area (TCSA).

CONCLUSIONS

The present study demonstrates that rootstock selection plays a decisive role in regulating vegetative growth, trunk development, and the formation of fruit-bearing structures in intensive apple orchards. Across both examined cultivars, 'Najdared' and 'Fuji San 51', significant differences were identified among the Geneva®, Budagovsky, and M.9-derived rootstocks, confirming their strong influence on tree architecture and early productivity potential. G.214 and M.9 RN29 consistently induced higher vegetative vigor, while B.9 and M.9 FL56 showed reduced growth. Differences were also evident in fruiting structure formation: G.16 and G.214 showed favorable tendencies, whereas G.11 was associated with weaker ramification ability and lower spur density. In several cases, higher vigor was accompanied by reduced formation of fruiting parts. These findings highlight the importance of appropriate rootstock–cultivar combinations for balancing vegetative and generative growth, thereby improving yield potential in intensive apple production systems.

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