




Tree vegetative and generative properties and their inter-correlations for prospective apple cultivars under two training systems for young trees

Ádám Csihon¹ · István Gonda¹ · Szilárd Szabó² · Imre J. Holb^{1,3} 

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Abstract

Little information is available on vegetative and generative performance of apple cultivars during the early growth of trees in orchards. The aim of this five-year study was to evaluate 2 vegetative (trunk cross sectional area (TCSA) and tree height (TH)) and 7 generative parameters (tree yield (TY), fruit number per tree (FNT), crop load (CL), fruit diameter (FD), shape index (SI), fruit surface color (FSC) and fruit color intensity (FCI)) and their inter-correlations (Pearson correlation, regression analyses and PCA) for young apple trees, on 9 apple cultivars ('Jugala', 'Galaval', 'Gala Venus Fengal', 'Gala Decarli-Fendeca', 'Gala Schnitzer (S) Schniga', 'Fuji September Wonder', 'Crimson Crisp (Co-op 39)', 'Jeromine', and 'Red Idared') in a slender spindle training system (2597 trees ha⁻¹) and on 4 apple cultivars ('Wilton's Red Jonaprince', 'Red Cap Valtod (S)', 'Early Red One', and 'Red Topaz') in a super spindle training system (5194 trees ha⁻¹) in Eastern Hungary. The strongest vegetative growth was observed in 'Red Idared', while the weakest was in 'Early Red One'. Most 'Gala' mutants showed high yields in all years, except for 'Galaval'. On the 6 year-old trees, the lowest tree yield was found in 'Fuji September Wonder' (8.2 kg tree⁻¹), while the highest was found in 'Gala Venus Fengal' (35.8 kg tree⁻¹). The lowest fruit number per tree (15 fruit tree⁻¹) was found in 'Jeromine', while the highest (222 fruit tree⁻¹) was in 'Gala Venus Fengal'. The highest crop load was found in 'Gala Venus Fengal' (12.72 fruit per cm² TCSA), while the lowest was in 'Jeromine' (2.13 fruit per cm² TCSA). The smallest fruit diameter (66.3 mm) was recorded in 'Gala Schnitzer (S) Schniga', while highest (93.6 mm) was in 'Red Idared'. The lowest shape index (0.73) was found in 'Red Topaz', while the highest (0.92) was in 'Red Idared'. The majority of the cultivars reached very good fruit surface color (80–100%). The lowest fruit surface color (40%) was observed in 'Gala Schnitzer (S) Schniga', while the highest (100%) was in 'Jeromine' and 'Early Red One'. The highest fruit color intensity was observed in most cultivars with the exception of 'Jeromine', 'Gala Schnitzer (S) Schniga' and 'Fuji September Wonder'. In addition, correlation and regression analyses revealed strong and significant ($p=0.05$) relationships between TH vs TCSA, TY vs TCSA, TH vs TY, TY vs FNT, and FCI vs FSC. PCA explained 87% of the total variance and PC1, PC2, PC3, and PC4 accounted for 33, 21, 20, and 13% of the variance, respectively, and correlated with TSCA, TH, TY and FNT; with FNT, CL and FS; with FSC and FCI; and with TH and SI, respectively. In conclusion, our study provides useful tree property data on prospective mutants/cultivars for growers/advisors in order to select the most suitable cultivars for establishing new orchards under climate conditions similar to central Europe.

Keywords Apple cultivars · Generative parameters · Training system · Vegetative parameters · Young tree

1 Introduction

Apple is one of the major fruit crops in the temperate zone, and its world production is around 87 million tons year⁻¹ grown in around 4.7 million ha (FAOSTAT 2019). The profitability of apple production is highly dependent on the cultivar genotype. Cultivars should ensure high annual yields with excellent quality and provide resistance to major diseases and pests, and must be attractive to consumers (e.g.

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✉ Imre J. Holb
holbimre@gmail.com

Extended author information available on the last page of the article

Fischer and Fisher 2008; Rozman 2015). Market acceptance of a cultivar is highly influenced by the fruit skin color. Among cultivar coloration, red skin color is most preferred, and a better fruit coloration increases the market value of a cultivar (e.g. Anton and Willen 2014). Therefore, breeding programs all over the world were aimed to improve the fruit skin color of the bicolor cultivars (e.g. Guerra and Sansavini 2012). Some mutants have already reached 100% fruit surface color, such as for ‘Gala’ sport; therefore, the total coloration combined with larger fruit diameter and earlier ripening time become the next priorities in breeding (Guerra and Sansavini 2012).

Fruit coloration is dependent on the genetic properties of the cultivars, but environmental factors also highly influence anthocyanin production (Naumann 1964; Proctor 1974). One of the essential factors for red color development is available light, as more light results in a higher amount of anthocyanin and red color in the fruit peel (e.g. Ubi et al. 2006). Fruit coloration is also dependent on other factors such as day and night differences in temperature (e.g. Blankenship 1987), altitude (Douglas 1983), training system and planting density (e.g. Wertheim et al. 1986; Weber 2001) and production technology elements including fruit thinning (e.g. Gonzalez et al. 2020), irrigation (e.g. Musacchi and Serra 2018), nutrition supply (e.g. Awad and Jager 2002) and ground cover (e.g. Schuhknecht et al. 2018). Various ecological circumstances and production technologies change not only fruit coloration of newly bred cultivars but can result in diverse vegetative and generative features under different climate conditions and production sites (e.g. Anton and Willen 2014).

Little information is available on vegetative and generative performance of apple cultivars during the early growth of trees in orchards. Therefore, the aim of this five-year

study was to evaluate two vegetative (trunk cross sectional area (TCSA) and tree height (TH)) and seven generative parameters (tree yield (TY), fruit number per tree (FNT), crop load (CL), fruit diameter (FD), shape index (SI), fruit surface color (FSC) and fruit color intensity (FCI)) of thirteen prospective apple cultivars (twelve mutants of popular cultivars and one disease-resistant ‘crisp’ cultivar) in two high-density training systems (slender spindle or super spindle) in a young (2–6 years old) apple orchard in Eastern Hungary. Inter-correlations (correlation, regression and principal component analyses) were also performed among the nine vegetative and generative parameters in order to explore the best relationships of the correlated parameters for the investigated cultivars/mutants and training systems.

2 Materials and methods

2.1 Location, weather, plant material and orchard management

A five-year study (2013–2017) was carried out in a commercial apple orchard in Eastern Hungary. The orchard was located in the city of Nyírbátor (47°50′54″N, 22°03′09″E). Orchard soil type was sandy soil with a humus content of 0.6–0.7%.

The main meteorological parameters were recorded by a Metos Agrometeorological Station located in the orchard. Monthly mean temperature ranged from –6.6 to 22.5 °C in the period of 2013–2017 (Table 1). In 2016, repeated late spring frosts in April caused a 100% yield loss; therefore, it was not possible to evaluate generative parameters in this year (Table 1). The annual mean precipitation ranged from 335 to 758 mm among the years (Table 1).

Table 1 The mean and minimum temperatures and precipitation (Nyírbátor, Hungary, 2013–2017)

Months	Mean temperature (°C)					Minimum temperature (°C)					Precipitation (mm)				
	2013	2014	2015	2016	2017	2013	2014	2015	2016	2017	2013	2014	2015	2016	2017
January	–1.0	2.5	0.6	–2.3	–6.6	–10.0	–5.3	–18.3	–16.1	–10.2	33.3	16.3	54.7	75.7	21.7
February	2.3	3.4	1.1	5.5	1.4	–8.2	–15.5	–11.4	–3.1	–1.2	47.0	23.1	23.1	86.2	29.1
March	2.8	8.4	5.8	6.4	8.4	–17.3	–5.3	–7.5	–5.7	2.5	102.4	10.9	14.7	42.5	25.7
April	11.8	12.0	10.0	12.5	10.1	–2.1	–2.0	–1.7	–3.7	4.0	38.3	13.1	22.7	11.4	42.2
May	16.4	15.5	15.6	15.7	16.3	6.9	–1.1	2.1	3.4	9.9	58.1	41.3	38.6	48.9	22.7
June	19.9	19.0	19.6	20.1	20.9	8.5	3.9	6.6	7.1	14.2	78.6	10.3	22.9	134.6	59.8
July	20.6	21.0	22.2	21.1	21.0	7.1	8.2	5.2	9.3	14.0	38.4	99.7	35.5	80.6	59.5
August	20.4	19.6	22.5	19.8	22.1	7.1	7.0	6.8	8.3	14.9	23.0	28.6	65.2	69.1	41.7
September	13.3	16.0	17.3	17.2	15.5	0.3	1.7	3.3	3.6	9.9	25.4	1.2	36.1	65.9	69.9
October	11.1	10.6	9.7	9.1	10.2	–6.7	–5.5	–0.4	–0.4	4.4	29.2	55.1	92.2	82.4	35.9
November	7.3	5.6	5.3	4.1	5.1	–9.7	–5.5	–3.9	–4.4	1.7	25.3	12.2	71.1	56.1	54.4
December	0.0	2.2	2.2	–2.3	2.1	–11.0	–15.8	–10.7	–9.6	0.1	1.1	23.6	18.8	4.9	92.3
Sum	–	–	–	–	–	–	–	–	–	–	500	335	495	758	555

Thirteen prospective apple cultivars, including twelve mutants of popular cultivars and one disease-resistant ‘crisp’ cultivar, were evaluated in the orchard (Table 2). All cultivars were grafted on M.9 rootstock and were planted in the autumn of 2010 or in the spring of 2011 (Table 2). Two training systems were used in the experimental orchard: slender spindle ($3.85 \times 1.0 \text{ m} = 2597 \text{ trees ha}^{-1}$) for nine cultivars and super spindle ($3.85 \times 0.5 \text{ m} = 5194 \text{ trees ha}^{-1}$) for four cultivars (Table 2). The cultivars ‘Red Jonaprince’, ‘Red Cap’, ‘Early Red One’ and ‘Red Topaz’ were planted in the more intensive training system (super spindle) according to the breeder recommendations.

Orchard management followed the European Integrated Fruit Production (IFP) guidelines. Fungicides and pesticides approved in IFP were used in the orchards with annual spray schedules from 13 to 21 pesticide applications during the growing seasons of 2013–2017. Winter pruning was performed each year during the dormant periods. Mechanical fruit thinning and summer pruning were performed in 2014, 2015 and 2017 for all cultivars after petal fall and in June, respectively. The orchard was irrigated each year with a drop irrigation system. For nutrient supply, an NPK fertilizer (Péti Kevert NPK, Nitrogénművek, GmbH, Pétfürdő, Hungary) was applied at mid-March each year at a dosage of 130 kg ha^{-1} active ingredient with a 10:15:15 N–P–K ratio. Grass between rows was cut three times in each year (mid-June, mid-July, and mid-August) with an orchard flail mower.

2.2 Assessment of vegetative parameters

Two vegetative parameters were assessed: trunk cross sectional area (TCSA) and tree height (TH). For each cultivar, 5 trees, replicated four times, were selected for assessments of both parameters. For trunk cross sectional area, diameter

of the trunk was measured with a Vernier caliper at the trunk halfway between the graft point and the first branches, and then this data was used to calculate trunk cross sectional area in cm^2 . Tree height in cm was recorded as the distance between the ground and the top of the tree not including the one year old shoots at the tree top. Both parameters were assessed each year after leaf fall in November.

2.3 Assessment of generative parameters

Seven generative parameters were assessed: tree yield (TY), fruit number per tree (FNT), crop load (CL), fruit diameter (FD), fruit shape index (FSI), fruit surface color (FSC) and fruit color intensity (FCI). For each cultivar, 5 trees, replicated four times, were selected for assessments of all parameters. All generative parameters were assessed at harvest in 2013–2015 and 2017. Harvest was done at the biological maturity stage of the cultivars determined by the starch-iodine test in 2013–2015 and 2017 (Table 3).

Fruit yield as kg tree^{-1} and fruit number per tree were recorded for each selected tree. After this, crop load was determined as fruit number per tree divided by trunk cross sectional area (fruit number per cm^2). Fruit diameter was determined as fruit diameter (mm) measured with a Vernier caliper. Fruit shape index (as 0–1) was determined as the ratio of fruit diameter and fruit height (mm). Fruit surface color was determined as 1–100% using an image analyses color scale. Fruit color intensity was used to express the intensity of red skin color using a scale ranging from 1 to 5.

Table 2 Some characteristics of the evaluated cultivars in the experimental orchard (Nyírbátor, Hungary, 2013–2017)

Cultivar	Country of origin	Pedigree	Year of planting	Training system
‘Jugala’	France	Mutant of ‘Mondial Gala’	2011 spring	Slender spindle
‘Galaval’	France	Mutant of ‘Gala Galaxy’	2011 spring	Slender spindle
‘Gala Venus Fengal’	Italy	Mutant of ‘Gala’	2011 spring	Slender spindle
‘Gala Decarli-Fendeca’	Italy	Mutant of ‘Gala’	2011 spring	Slender spindle
‘Gala Schnitzer (S) Schniga’	Italy	Mutant of ‘Royal Gala’	2010 autumn	Slender spindle
‘Fuji September Wonder’	USA	Mutant of ‘Yataka Fuji’	2011 spring	Slender spindle
‘Crimson Crisp’	USA	PCWF2-134 × PRI 669–205	2011 spring	Slender spindle
‘Jeromine’	France	Mutant of ‘Early Red One’	2010 autumn	Slender spindle
‘Red Idared’	USA	Mutant of ‘Idared’	2010 autumn	Slender spindle
‘Wilton’s Red Jonaprince’	Holland	Mutant of ‘Jonagold’	2011 spring	Super spindle
‘Red Cap’	USA	Mutant of ‘Red Delicious’	2011 spring	Super spindle
‘Early Red One’	USA	Mutant of ‘Red King’	2011 spring	Super spindle
‘Red Topaz’	Czech Republic	Mutant of ‘Topaz’	2011 spring	Super spindle

Table 3 Time of harvest (day month⁻¹) at the experimental orchard according to the starch-iodine test (Nyírbátor, Hungary, 2013–2015, and 2017)

Cultivars	2013	2014	2015	2017
‘Jugala’	3/9	24/8	30/8	20/8
‘Galaval’	30/8	24/8	30/8	22/8
‘Gala Venus Fengal’	27/8	26/8	4/9	25/8
‘Gala Decarli-Fendeca’	27/8	26/8	4/9	25/8
‘Gala Schnitzer (S) Schniga’	3/9	29/8	11/9	30/8
‘Fuji September Wonder’	19/9	11/9	21/9	12/9
‘Crimson Crisp’	12/9	11/9	16/9	19/9
‘Jeromine’	13/9	17/9	15/9	12/9
‘Red Idared’	90/9	3/10	13/10	5/10
‘Wilton’s Red Jonaprince’	13/9	17/9	24/9	20/9
‘Red Cap Valtod (S)’	15/9	20/9	24/9	22/9
‘Early Red One’	13/9	17/9	24/9	15/9
‘Red Topaz’	15/9	28/9	6/10	3/10

2.4 Data analyses

2.4.1 ANOVA

Data of each parameter were averaged to obtain a single value for each cultivar, training system and year. Data were subjected to analyses of variance (ANOVA) in order to determine the effect of cultivars and years; and their interactions were assessed on the nine parameters, separately for slender spindle and super spindle training systems. Then, within the two training systems, significant F tests ($p=0.05$) were followed by a least significant difference (LSD) test for each year and cultivar in order to compare the means of all vegetative and generative parameters using $LSD_{0.05}$ values. For the analyses, Genstat Release 9.1 (Lawes Agricultural Trust, IACR, Rothamsted, UK) was used.

2.4.2 Correlation and linear regression analyses

Relationships among all vegetative and generative parameters were analysed by Pearson correlation coefficients (r) and their associated significance levels ($p=0.05$) were separately determined for slender spindle and super spindle training systems. Then the strongest significantly correlated pairs were determined for both training systems. Then the Pearson correlation coefficient (r) of these significant pair variables was also determined for the thirteen cultivars, separately. In addition, the strongest significantly correlated pairs were plotted against each other and linear regression functions were then fitted for slender spindle and super spindle training systems. Then a t test was used to determine whether the regression slopes were significantly ($p=0.05$) different from slender spindle to super spindle training systems.

For the analyses, Genstat Release 9.1 (Lawes Agricultural Trust, IACR, Rothamsted, UK) was used. Pearson correlation matrixes were visualized with R package `corrplot` (Wei and Simko 2021).

2.4.3 Principal component analyses

A standardized Principal Component Analysis (PCA) was prepared using the correlation matrix with the variables of trunk cross sectional area, tree height, tree yield, fruit number per tree, crop load, fruit diameter, fruit shape index, fruit surface color and fruit color intensity. The values of all parameters were transformed to z-scores in order to standardize the variables. During performing PCA, model fits were also tested using the value of Root Mean Square Residual (RMSR) (Basto and Pereira 2012). Principal Components (PCs) were shown in biplot diagrams. R 4.04 (R Core Team 2021) with the `psych` (Revelle 2015), `FactoMiner` (Lê et al. 2008) and `factoextra` (Kassambara and Mundt 2019) packages were used to perform PCA.

3 Results

3.1 ANOVA for vegetative and generative parameters

Analysis of variance (ANOVA) on the parameters of trunk cross sectional area, tree height, tree yield, fruit number per tree, crop load, fruit diameter, fruit shape index, fruit surface color and fruit color intensity showed that there were significant ($p < 0.05$) effects for cultivars and years in the two training systems (Table 4). Interactions for the treatment effects were non-significant (Table 4). According to ANOVA, the data of all vegetative and generative parameters were presented separately for cultivars and years in the two training systems.

3.2 Vegetative parameters of apple cultivars

The trunk cross sectional area values ranged from 4.8 to 41.4 cm² in the five-year period for the thirteen cultivars and two training systems (Table 5). The yearly trunk cross sectional area ranges were between 4.8 and 14.3, 5.9 and 16.3, 8.5 and 22.1, 12.3 and 33.5, and 14.5 and 41.4 cm² in 2013, 2014, 2015, 2016, and 2017, respectively (Table 5). The trunk cross sectional area values continuously increased for all cultivars with years from the tree age of 2 to 6 years old. By the year 2017 (6 year old trees), the lowest trunk cross sectional area value (14.5 cm²) was observed in ‘Early Red One’ in the super spindle training system, while the highest trunk cross sectional area value (41.4 cm²) was found in ‘Red Idared’ in the slender spindle training system (Table 5).

Table 4 Mean squares from the variance analyses of apple cultivars and years in slender spindle and super spindle training systems (Nyírbátor, Hungary, 2013–2017)

Slender spindle training system											
S. of variation	df	TSCA	TH	df	TY	FNT	CL	FD	SI	FSC	FCI
Year (Y)	4	2,815.4 **	72,621.8**	3	830.1 **	17,610.1**	60.5**	353.6 *	0.021 **	182.3 *	1.6 *
Cultivar (C)	8	732.4 *	34,130.7**	8	571.4 *	31,259.5**	66.6**	597.5 **	0.012 *	4638.9 **	4.7 **
Y x C	32	57.6 ns	769.1 ns	24	72.3 ns	1,573.8 ns	12.1 ns	23.4 ns	0.001 ns	83.1 ns	0.051 ns
Error	180	14.1	83.4	144	11.7	344.6	1.8	3.2	<0.001	3.6	0.011
Slender spindle training system											
S. of variation	df	TSCA	TH	df	TY	FNT	CL	FD	SI	FSC	FCI
Year (Y)	4	625.8 **	31,656.8**	3	241.3 **	4,585.4 **	23.1 **	40.4 *	0.006 *	558.3 *	0.54 *
Cultivar (C)	3	588.1 **	51,182.2**	3	192.1 *	3,635.8 *	10.8 *	162.2 **	0.069 **	2008.9 **	3.1 **
Y x C	12	33.1 ns	1,021 ns	9	22.2 ns	940.9 ns	1.4 ns	11.9 ns	0.001 ns	45.9 ns	0.16 ns
Error	80	10.3	314.1	64	6.7	23.2	0.89	0.79	<0.001	2.4	0.031

S. of variation: Source of variation

TSCA: trunk cross sectional area, TH: tree height, TY: tree yield, FNT: fruit number per tree, CL: crop load, FD: fruit diameter, SI: shape index, FSC: fruit surface color and FCI: fruit color intensity; df: degree of freedom; ns: nonsignificant; *: statistically significant at $p < 0.05$, **: statistically significant at $p < 0.01$

TSCA and TH data contained five years (2013–2017); data of all other parameters contained four years (2013–2015, 2017) due to frost damage in 2016

Table 5 Trunk cross sectional area (TSCA (cm²)) and tree height (TH (cm)) of thirteen apple cultivars grown in slender spindle and super spindle training systems (Nyírbátor, Hungary, 2013–2017)

Cultivars	Trunk cross sectional area (cm ²)					Tree height (cm)				
	2013	2014	2015	2016	2017	2013	2014	2015	2016	2017
<i>Slender spindle</i>										
‘Jugala’	13.0 ^{xd}	16.6 ^x	20.2 ^{xd}	33.1 ^x	35.7 ^{xd}	216 ^y	282 ^x	322 ^x	328 ^{yx}	328 ^{yx}
‘Galaval’	11.9 ^y	16.1 ^x	19.5 ^{yx}	28.0 ^{yx}	36.3 ^{xd}	256 ^x	302 ^x	328 ^x	328 ^{yx}	328 ^{yx}
‘Fengal’	11.1 ^{yx}	16.3 ^x	22.1 ^d	33.5 ^x	38.6 ^d	286 ^d	355 ^d	368 ^d	350 ^{xd}	350 ^{xd}
‘Fendeca’	11.3 ^{yx}	14.2 ^{yx}	16.1 ^y	21.8 ^y	23.2 ^z	243 ^x	276 ^x	296 ^x	326 ^{yx}	326 ^y
‘Schniga’	14.3 ^d	16.0 ^y	16.9 ^y	23.6 ^y	27.2 ^y	253 ^x	300 ^x	316 ^x	320 ^y	320 ^{zy}
‘Fuji SW’	4.9 ^z	6.5 ^z	9.1 ^z	13.6 ^z	15.6 ^z	167 ^z	212 ^z	218 ^z	262 ^z	300 ^z
‘Crimson Crisp’	10.0 ^y	13.4 ^y	17.3 ^{yx}	26.0 ^y	29.6 ^{yx}	251 ^x	346 ^y	360	360 ^d	360 ^d
‘Jeromine’	5.9 ^z	7.5 ^z	9.8 ^z	12.7 ^z	15.9 ^z	182 ^z	237 ^y	246 ^{zy}	274 ^z	298 ^z
‘Red Idared’	10.0 ^y	14.4 ^{yx}	17.8 ^{yx}	29.3 ^{xd}	41.4 ^d	187 ^z	236 ^{zy}	252 ^y	318 ^y	348
LSD _{0.05}	2.3	2.6	3.2	6.2	7.1	23.5	28.4	32.1	24.5	22.7
<i>Super spindle</i>										
‘Red Jonaprince’	8.2 ^y	15.0 ^x	16.6 ^y	28.2 ^y	29.9 ^y	198 ^y	291 ^y	368 ^y	356 ^y	356 ^x
‘Red Cap’	4.8 ^z	5.9 ^z	8.6 ^z	12.3 ^z	14.8 ^z	183 ^{zy}	224 ^z	230 ^z	250 ^z	288 ^y
‘Early Red One’	4.9 ^z	5.9 ^z	8.5 ^z	12.8 ^z	14.5 ^z	177 ^z	213 ^z	222 ^z	228 ^z	250 ^z
‘Red Topaz’	6.7 ^{zy}	9.7 ^y	10.1 ^z	14.9 ^z	19.1 ^z	181 ^{zy}	209 ^z	220 ^z	234 ^z	260 ^{zy}
LSD _{0.05}	2.0	2.3	2.9	5.9	6.7	20.3	24.2	30.6	26.5	32.1

Values followed by the same letter are not significantly different according to LSD test ($p = 0.05$). LSD_{0.05} = least significant differences at $p = 0.05$ level. ‘Fengal’: ‘Gala Venus Fengal’, ‘Fendeca’: ‘Gala Decarli-Fendeca’, ‘Schniga’: ‘Gala Schnitzer (S) Schniga’, ‘Fuji SW’: ‘Fuji September Wonder’, and ‘Red Jonaprince’: ‘Wilton’s Red Jonaprince’

In the five-year period, the tree height values ranged from 167 to 360 cm for the cultivars/training systems (Table 5). The yearly tree height ranged from 167 to 286, 209 to 355,

218 to 368, 228 to 360, and 250 to 360 cm in 2013, 2014, 2015, 2016, and 2017, respectively (Table 5). By the year 2017, the lowest tree height was found in ‘Fuji September

Wonder', while the highest was in 'Crimson Crisp', both in the slender spindle training system (Table 5). Most cultivars reached the optimal tree height (3.0–3.5 m) after 4–5 years, except for 'Fuji SW', 'Jeromine', 'Red Idared', 'Red Cap Valto (S)', 'Early Red One' and 'Red Topaz'. Cultivars 'Red Cap Valto (S)', 'Early Red One' and 'Red Topaz' in the super spindle canopy were not able to reach the optimal height even at 6 years old (Table 5).

3.3 Generative parameters of apple cultivars

In the assessed period, the tree yield ranged between 2.4 and 35.8 kg tree⁻¹ corresponding to 6.3 and 93.1 t ha⁻¹ (Table 6). By the year 2017, the lowest tree yield was found in 'Fuji September Wonder', (8.2 kg tree⁻¹, i.e. 21.3 t ha⁻¹) while the highest tree yield was in 'Gala Venus Fengal' (35.8 kg tree⁻¹, i.e. 93.1 t ha⁻¹), in both cases in the slender spindle training system (Table 6). The sum of the four-year yield was the lowest in 'Fuji September Wonder' (24.6 kg tree⁻¹, 64.0 t ha⁻¹) and the highest in 'Gala Venus Fengal' (95.6 kg tree⁻¹, 248.4 t ha⁻¹). Trees trained to super spindle produced considerable fruit yield in 'Wilton's Red Jonaprince' and 'Red Topaz' (Table 6).

The fruit number per tree ranged between 15 and 222 fruit tree⁻¹ in the assessed period (Table 6). The lowest fruit number (15 fruit tree⁻¹) was found in 'Jeromine' in 2013 in

the slender spindle training system while the highest (222 fruit tree⁻¹) was in 'Gala Venus Fengal' in 2017, also in the slender spindle training system (Table 6). By the year 2017, more than 100 fruit tree⁻¹ was observed in all 'Gala' mutants ('Jugala', 'Galaval', 'Gala Venus Fengal', 'Gala Decarli-Fendeca', and 'Gala Schnitzer (S) Schniga') and in 'Fuji September Wonder' in the slender spindle training system (Table 6).

During the assessed period, the highest crop load was found in 'Gala Venus Fengal' in 2013 on the 3-year-old trees (12.72 fruit per cm² TCSA), while the lowest was in 'Jeromine' (2.13 fruit per cm² TCSA) in 2017 on the 6-year-old trees. Generally, cultivars with lower fruit number per tree (e.g. 'Fuji September Wonder', 'Early Red One', and 'Red Cap Valto (S)') showed medium or high crop loads (Table 6).

Most cultivars presented the smallest fruit diameter in 2013 (Table 7), when fruit thinning was not applied. During the assessed period, the smallest fruit diameter (66.3 mm) was found in 'Gala Schnitzer (S) Schniga' in 2013, while highest (93.6 mm) was in 'Red Idared' in 2014 (Table 7). Fruit diameter of all cultivars reached the market required minimum of 70 mm by 2017.

During the assessed period, the lowest shape index (0.73) was found in 'Red Topaz' in 2013 and 2014, while the highest (0.92) was in 'Gala Schnitzer (S) Schniga' in 2017

Table 6 Tree yield (TY (kg tree⁻¹)), fruit number per tree (FNT) and crop load (CL (fruit number per cm² TCSA)) of thirteen apple cultivars grown in slender spindle and super spindle training systems (Nyírbátor, Hungary, 2013–2017)

Cultivar	Tree yield (kg tree ⁻¹)					Fruit number per tree				Crop load (fruit number per cm ²)			
	2013	2014	2015	2017	∑	2013	2014	2015	2017	2013	2014	2015	2017
<i>Slender spindle</i>													
'Jugala'	10.7 ^y	14.9 ^{xw}	16.7 ^x	21.2 ^x	63.4	81 ^x	83 ^y	111 ^{wv}	113 ^{yx}	6.02 ^{yx}	5.22 ^{yx}	5.15 ^{zy}	2.13 ^z
'Galaval'	9.9 ^y	11.3 ^y	12.4 ^{yx}	20.0 ^{yx}	53.6	86 ^x	70 ^y	85 ^y	112 ^{yx}	7.12 ^{yx}	4.31 ^{zy}	4.53 ^{zy}	3.15 ^z
'Fengal'	17.7 ^x	15.8 ^{xw}	26.3 ^w	35.8 ^w	95.6	131 ^w	88 ^y	191 ^u	222 ^v	12.72 ^u	6.00 ^{xw}	8.23 ^x	5.92 ^{yx}
'Fendeca'	16.7 ^x	12.6 ^{yx}	14.2 ^{yx}	25.8 ^x	69.3	134 ^w	82 ^y	106 ^{xwv}	153 ^w	11.07 ^{vu}	6.26 ^{xw}	6.35 ^{yx}	7.31 ^x
'Schniga'	12.4 ^y	16.3 ^w	16.3 ^x	20.1 ^{yx}	65.1	122 ^w	127 ^x	124 ^v	124 ^x	9.72 ^{wv}	9.36 ^v	7.39 ^x	4.94 ^y
'Fuji SW'	4.0 ^z	5.9 ^z	6.5 ^z	8.2 ^z	24.6	34 ^{zy}	33 ^z	44 ^z	104 ^{yx}	7.4 ^{xw}	6.84 ^{xw}	5.35 ^{zy}	6.83 ^x
'Crimson Crisp'	6.5 ^z	14.6 ^{xw}	15.1 ^{yx}	7.1 ^z	43.2	43 ^y	86 ^y	94 ^{xw}	85 ^y	4.38 ^{zy}	7.16 ^w	5.30 ^{zy}	2.93 ^z
'Jeromine'	2.4 ^z	6.9 ^z	n.d.	14.8 ^y	24.2	15 ^z	39 ^z	n.w	32 ^z	2.48 ^z	5.33 ^{yxw}	n.d.	2.13 ^z
'Red Idared'	6.2 ^z	12.9 ^{yx}	11.8 ^y	24.9 ^x	55.8	37 ^y	46 ^z	65 ^z	94 ^{yx}	3.71 ^{zy}	3.52 ^z	3.96 ^z	2.33 ^z
LSD _{0.05}	2.9	3.2	4.3	6.3	–	21	22	25	33	2.4	1.9	2.0	1.4
<i>Super spindle</i>													
'Red Jonaprince'	9.0 ^y	12.8 ^x	18.0 ^y	15.0 ^{zy}	54.9	43 ^y	50 ^z	95 ^y	76 ^y	5.01 ^z	4.2 ^z	6.07 ^z	3.82 ^{zy}
'Red Cap'	4.9 ^z	n.d.	7.1 ^z	12.9 ^{zy}	24.8	25 ^z	n.d.	33 ^z	67 ^{zy}	5.84 ^{zy}	n.d.	4.56 ^z	4.65 ^{zy}
'Early Red One'	5.2 ^z	6.5 ^z	6.9 ^z	11.7 ^z	30.3	34 ^{zy}	41 ^z	36 ^z	66 ^{zy}	7.43 ^y	6.05 ^y	4.51 ^z	4.97 ^y
'Red Topaz'	5.6 ^z	9.4 ^y	15.0 ^y	16.3 ^y	46.3	40 ^y	58 ^z	104 ^y	43 ^z	6.46 ^{zy}	6.47 ^y	10.40 ^y	2.62 ^z
LSD _{0.05}	2.5	2.8	3.9	4.2	–	12	18	21	24	2.0	1.6	2.1	1.2

Values followed by the same letter are not significantly different according to LSD test ($p=0.05$). LSD_{0.05}=least significant differences at $p=0.05$ level. n.d.: no data available; 'Fengal': 'Gala Venus Fengal', 'Fendeca': 'Gala Decarli-Fendeca', 'Schniga': 'Gala Schnitzer (S) Schniga', 'Fuji SW': 'Fuji September Wonder', and 'Red Jonaprince': 'Wilton's Red Jonaprince'

Table 7 Fruit diameter (FD (mm)), shape index (SI), fruit surface color (FSC (%)) and fruit color intensity (FCI) (1–5) of thirteen apple cultivars grown in slender spindle and super spindle training systems (Nyírbátor, Hungary, 2013–2017)

Cultivar	Fruit diameter (mm)				Shape index				Fruit surface color (%)				Fruit color intensity (1–5)			
	2013	2014	2015	2017	2013	2014	2015	2017	2013	2014	2015	2017	2013	2014	2015	2017
<i>Slender spindle</i>																
‘Jugala’	68.7 ^{zy}	74.7 ^x	72.0 ^y	78.2 ^{xw}	0.84 ^{xw}	0.87 ^{yx}	0.84 ^{yx}	0.88 ^{yx}	68 ^z	76 ^y	69 ^{xw}	62 ^y	3.9 ^y	4.9 ^x	4.1 ^z	4.0 ^x
‘Galaval’	68.6 ^z	74.8 ^x	71.2 ^y	76.8 ^{zyx}	0.83 ^x	0.86 ^y	0.84 ^{yx}	0.88 ^{yx}	86 ^x	90 ^x	82 ^v	89 ^w	5.0 ^w	5.0 ^x	4.4 ^y	4.8 ^v
‘Fengal’	69.5 ^y	75.2 ^x	71.0 ^{zy}	73.9 ^z	0.86 ^{wv}	0.89 ^{xw}	0.84 ^{yx}	0.90 ^{xw}	79 ^y	89 ^x	74 ^w	74 ^x	5.0 ^w	5.0 ^x	4.4 ^y	4.4 ^w
‘Fendeca’	67.5 ^{zy}	72.0 ^y	69.8 ^{zy}	75.0 ^{zy}	0.87 ^{vu}	0.90 ^w	0.85 ^x	0.88 ^{yx}	87 ^x	90 ^x	84 ^{vu}	91 ^w	5.0 ^w	5.0 ^x	4.6 ^y	4.8 ^v
‘Schniga’	66.4 ^z	66.3 ^z	67.4 ^z	73.5 ^z	0.89 ^u	0.87 ^{yx}	0.84 ^y	0.92 ^w	68 ^z	40 ^z	58 ^y	56 ^y	3.5 ^z	3.6 ^z	4.0 ^z	3.5 ^y
‘Fuji SW’	68.9 ^{zy}	78.1 ^w	71.7 ^y	74.0 ^z	0.80 ^y	0.82 ^z	0.82 ^{zy}	0.85 ^z	75 ^{zy}	45 ^z	50 ^z	41 ^z	4.3 ^x	4.2 ^y	3.9 ^z	2.9 ^z
‘Crimson Crisp’	73.2 ^x	75.1 ^x	71.6 ^y	76.0 ^{zyx}	0.84 ^{xw}	0.86 ^y	0.90 ^w	0.89 ^x	71 ^z	86 ^x	90 ^u	86 ^w	4.7 ^w	5.0 ^x	5.0 ^x	4.9 ^v
‘Jeromine’	76.6 ^w	80.7 ^v	n.d.	81.5 ^w	0.82 ^x	0.85 ^y	n.d.	0.89 ^x	95 ^w	100 ^w	n.d.	100 ^v	5.0 ^w	5.0 ^x	n.d.	5.0 ^v
‘Red Idared’	85.0 ^v	93.6 ^u	81.5 ^x	87.1 ^v	0.75 ^z	0.82 ^z	0.80 ^z	0.86 ^{zy}	74 ^{zy}	85 ^x	60 ^y	76 ^x	3.9 ^y	5.0 ^x	4.4 ^y	4.4 ^w
LSD _{0.05}	3.0	2.3	2.7	2.5	0.02	0.02	0.02	0.02	7.1	6.6	7.7	8.6	0.2	0.3	0.3	0.3
<i>Super spindle</i>																
‘Red Jonaprince’	81.5 ^y	88.2 ^y	80.7 ^y	81.7 ^y	0.83 ^y	0.86 ^x	0.86 ^y	0.87 ^y	79 ^{zy}	83 ^y	85 ^y	88 ^y	4.5 ^y	5.0 ^z	5.0 ^y	4.4 ^z
‘Red Cap’	81.0 ^y	n.d.	81.8 ^y	78.8 ^z	0.86 ^x	n.d.	0.85 ^y	0.89 ^{yx}	73 ^z	n.d.	97 ^x	89 ^y	3.2 ^z	n.d.	5.0 ^y	4.5 ^{zy}
‘Early Red One’	76.7 ^z	78.4 ^z	81.1 ^y	78.3 ^z	0.82 ^y	0.83 ^y	0.84 ^y	0.90 ^x	90 ^x	99 ^x	98 ^x	96 ^x	4.8 ^x	5.0 ^z	5.0 ^y	4.7 ^y
‘Red Topaz’	73.9 ^z	78.5 ^z	72.1 ^z	80.8 ^{zy}	0.73 ^z	0.73 ^z	0.75 ^z	0.75 ^z	85 ^{yx}	74 ^z	59 ^z	67 ^z	5.0 ^x	4.9 ^z	4.1 ^z	4.6 ^{zy}
LSD _{0.05}	3.0	2.1	2.6	2.1	0.02	0.02	0.02	0.02	6.9	7.0	7.7	8.3	0.2	0.3	0.3	0.3

Values followed by the same letter are not significantly different according to LSD test ($p=0.05$). LSD_{0.05}=least significant differences at $p=0.05$ level. n.d.: no data; ‘Fengal’: ‘Gala Venus Fengal’, ‘Fendeca’: ‘Gala Decarli-Fendeca’, ‘Schniga’: ‘Gala Schnitzer (S) Schniga’, ‘Fuji SW’: ‘Fuji September Wonder’, and ‘Red Jonaprince’: ‘Wilton’s Red Jonaprince’

(Table 7). Most cultivars showed a globular shape (shape index between 0.85 and 0.90), with the exception of ‘Red Topaz’, which displayed flat fruit with a shape index of 0.73–0.75 (Table 7). Fruit shape of ‘Red Idared’ considerably varied among the years as the shape index ranged between 0.75 and 0.86 (Table 7).

During the assessed period, the lowest fruit surface color (40%) was found in ‘Gala Schnitzer (S) Schniga’ in 2014, while the highest (100%) was in ‘Jeromine’ in 2014 and 2017 (Table 7). Fruit surface color was below 80% for all years in the case of ‘Gala Schnitzer (S) Schniga’ and ‘Fuji September Wonder’. During the assessed period, the best colored cultivars were ‘Jeromine’ and ‘Early Red One’.

During the assessed period, the lowest fruit color intensity (2.9) was found in ‘Fuji September Wonder’ in 2017, while the highest (5) was found in almost all cultivars at least in one year, with the exception of ‘Jugala’, ‘Gala Schnitzer (S) Schniga’ and ‘Fuji September Wonder’ (Table 7).

3.4 Correlation and regression analyses among vegetative and generative parameters

Pearson correlation coefficient (r) was the highest ($r=0.81$) between FNT and TY in the slender spindle training system (Fig. 1AB). The six correlation pairs were significant ($p=0.05$) for both training systems; 5 parameter pairs

correlated positively (TH vs TCSA, TY vs TCSA, TH vs TY, TY vs FNT, and FSI vs FSC), and one negatively (CL vs FS) (Fig. 1AB). These six correlation pairs also showed strong and significant ($p=0.05$) relationships for most of the thirteen cultivars with the best overall correlation values in ‘Jugala’, ‘Fendeca’, ‘Red Cap’, ‘Early Red One’ and ‘Red Topaz’ (Table 8).

The linear regression analysis showed significant relationships for all 6 pair-variables with $r=0.732$ – 0.916 , $p=0.04$ – 0.001 and with $r=0.711$ – 0.899 , $p=0.02$ – 0.001 for the slender spindle and super spindle training systems, respectively. The slopes of the 6 pair-variables for the slender spindle training systems were not significantly ($P=0.05$) different from the slopes for the super spindle training systems. In the case of TH vs TCSA relationships, a relatively high tree height was observed for almost all TCSA values (Fig. 2A). In the case of TY vs TCSA relationships, the majority of TCSA values were directly proportional to the increase of tree yield (Fig. 2B). In the case of TY vs TH relationships, the speed of the yield increase was not directly proportional to the increase of tree height (Fig. 2C). In the case of FNT vs TY relationships, the increase of fruit number was directly proportional to the increase of tree yield (Fig. 2D). In the case of FCI vs FSC relationships, the two parameters were directly proportional to each other (Fig. 2E). In the case of FS vs CL relationships, increasing

Fig. 1 Pearson correlation coefficients (r) among two vegetative and seven generative parameters in slender spindle (a) and super spindle (b) training systems (Nyírbátor, Hungary, 2013–2017). Values of Pearson correlation coefficient above 0.54 were significant at $p=0.05$. TSCA: trunk cross sectional area, TH: tree height, TY: tree yield, FNT: fruit number per tree, CL: crop load, FD: fruit diameter, SI: shape index, FSC: fruit surface color and FCI: fruit color intensity

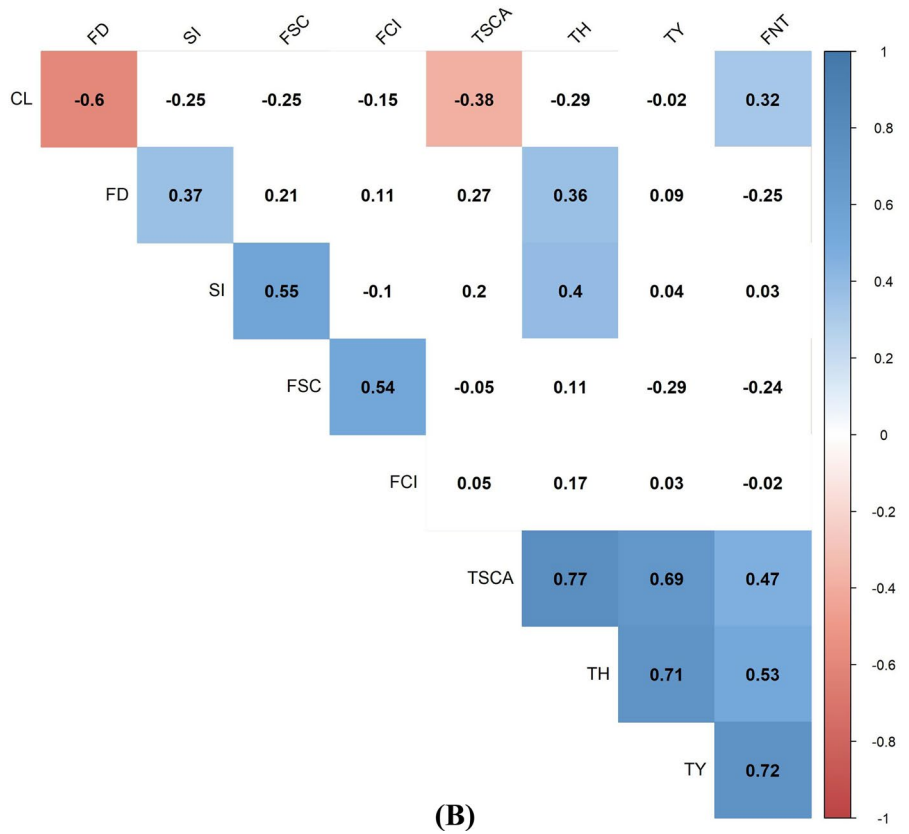
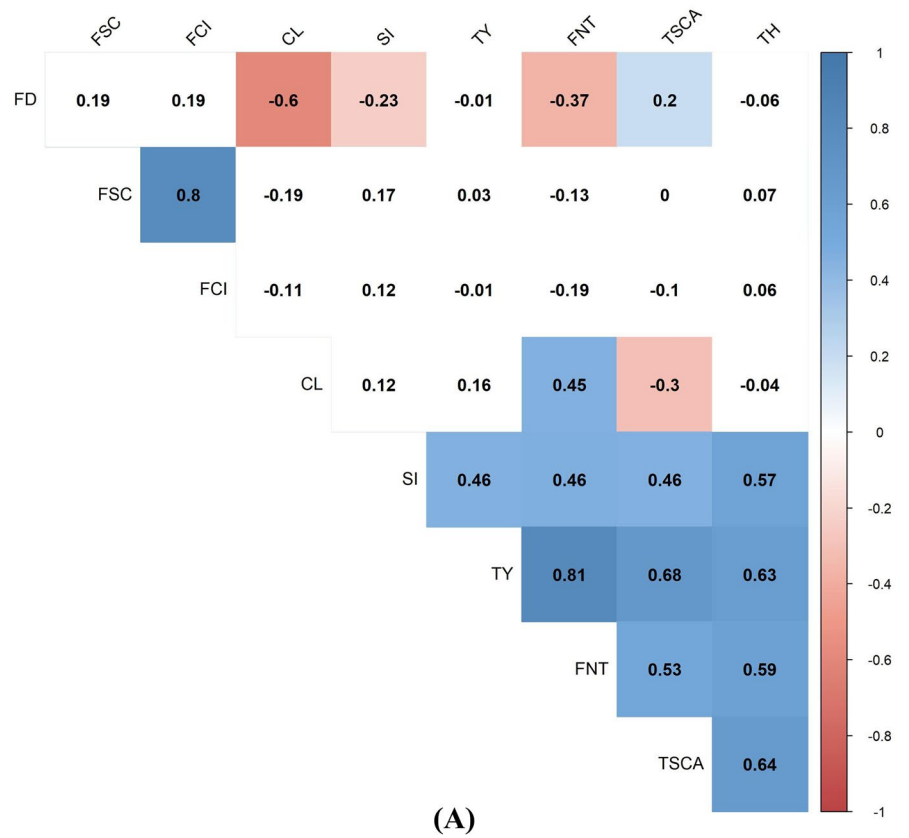


Table 8 Pearson correlation coefficients (r) of the five best correlated pairs of measured parameters for the thirteen apple cultivars (Nyírbátor, Hungary, 2013–2017). Significant ($p=0.05$) relationships are indicated as bold. TCSA: Trunk cross sectional area

Cultivars/ Correlation pairs	TCSA vs Tree height	TCSA vs Tree yield	Tree height vs Tree yield	Fruit number per tree vs Tree yield	Fruit colour intensity vs Fruit surface colour	Crop load vs Fruit diam- eter
‘Jugala’	0.70	0.71	0.69	0.80	0.60	−0.60
‘Galaval’	0.46	0.84	0.50	0.78	0.59	−0.51
‘Fengal’	0.44	0.85	0.32	0.86	0.60	−0.63
‘Fendeca’	0.66	0.61	0.55	0.86	0.67	−0.58
‘Schniga’	0.32	0.48	0.55	0.57	0.45	−0.49
‘Fuji SW’	0.79	0.40	0.56	0.71	0.45	−0.48
‘Crimson Crisp’	0.59	−0.15	0.48	0.58	0.66	0.45
‘Jeromine’	0.76	0.80	0.88	0.24	no data	−0.45
‘Red Idared’	0.91	0.82	0.89	0.86	0.41	−0.49
‘Red Jonaprince’	0.65	0.42	0.75	0.70	0.06	−0.45
‘Red Cap’	0.79	0.88	0.83	0.92	0.97	−0.87
‘Early Red One’	0.73	0.80	0.68	0.95	0.69	−0.74
‘Red Topaz’	0.67	0.73	0.72	0.55	0.84	−0.82

‘Fengal’: ‘Gala Venus Fengal’, ‘Fendeca’: ‘Gala Decarli-Fendeca’, ‘Schniga’: ‘Gala Schnitzer (S) Schniga’, ‘Fuji SW’: ‘Fuji September Wonder’, and ‘Red Jonaprince’: ‘Wilton’s Red Jonaprince’

Significant ($p = 0.05$) relationships are indicated as bold

crop load values resulted in slight decreases of fruit diameter for both training systems (Fig. 2E).

3.5 Principal component analyses among vegetative and generative parameters

PCA explained 87% of the total variance and the PCs had been justified. The RMSR was 0.05 indicating good fit. PC1 accounted for 33% of the variance and correlated with TCSA, TH, TY, and FNT (Table 9). PC2 accounted for 21% of the variance and correlated with FNT, CL and FS. PC3 accounted for 20% of the variance and correlated with FSC and FCI. PC4 accounted for 13% of the variance and correlated with TH and SI (Table 9).

According to the biplot figure for the training systems, PC1 and PC2 axes played considerable roles for both training systems (slender and super spindle) (Fig. 3A). However, the biplot figure showed that the PC2 axis was more dominant for the super spindle training system while both PC1 and PC2 axes were dominant for the slender spindle training system (Fig. 3A).

According to the biplot figure for cultivars, the PC1 and PC2 axes played various roles for the thirteen cultivars (Fig. 3BC). According to the biplot figure for the nine cultivars in the slender spindle training system, the PC1 axis was more dominant for ‘Fuji September Wonder’ and ‘Gala Schnitzer (S) Schniga’, and the PC2 axis for ‘Jeromine’ (Fig. 3B); while both PC1 and PC2 axes were dominant for the remaining cultivars (‘Crimson Crisp-Co-op 39’, ‘Gala Decarli-Fendeca’, ‘Gala Venus Fengal’, ‘Galaval’, ‘Jugala’,

and ‘Red Idared’) (Fig. 3B). According to the biplot figure for the four cultivars in the super spindle training system, both PC1 and PC2 axes were dominant for ‘Red Cap Valtod (S)’ and ‘Red Topaz’ while the PC2 axis was more dominant for ‘Early Red One’ and ‘Wilton’s Red Jonaprince’ (Fig. 3C).

Long arrows’ length and proximity of the variables of TCSA, TH, FS, TY, FNT, CL, FSC, and FCI indicated a strong decisive role of both PC groups. All these results indicated strong associations among tree vegetative and generative properties (Fig. 3ABC).

4 Discussion

In this study, we evaluated tree vegetative and generative properties of thirteen prospective apple cultivars/mutants on 2- to 6-year-old trees trained to slender or super spindle training systems under natural environmental conditions. Data showed clear differences among years and cultivars for the two training systems (Tables 5, 6, 7 and 8). Correlation and regression analyses revealed strong and significant ($p=0.05$) relationships between TH vs TCSA, TY vs TCSA, TH vs TY, TY vs FNT, and FCI vs FSC in both training systems (Tables 9; Figs. 1 and 2). In addition, PCA indicated strong associations among tree vegetative and generative properties for the cultivars and training systems (Table 9 and Fig. 3).

In the case of vegetative parameters, most cultivars trained to slender spindle reached higher trunk thickness

Fig. 2 Relationship between trunk cross sectional area (TSCA) and tree height (TH) (a), TSCA and tree yield (TY) (b), TH and TY (c), TY and fruit number per tree (FNT) (d), fruit surface colour (FSC) and fruit colour intensity (FCI) (e), crop load (CL) and fruit diameter (FD) (f) of thirteen apple cultivars in slender spindle and super spindle training systems (Nyírbátor, Hungary, 2013–2017)

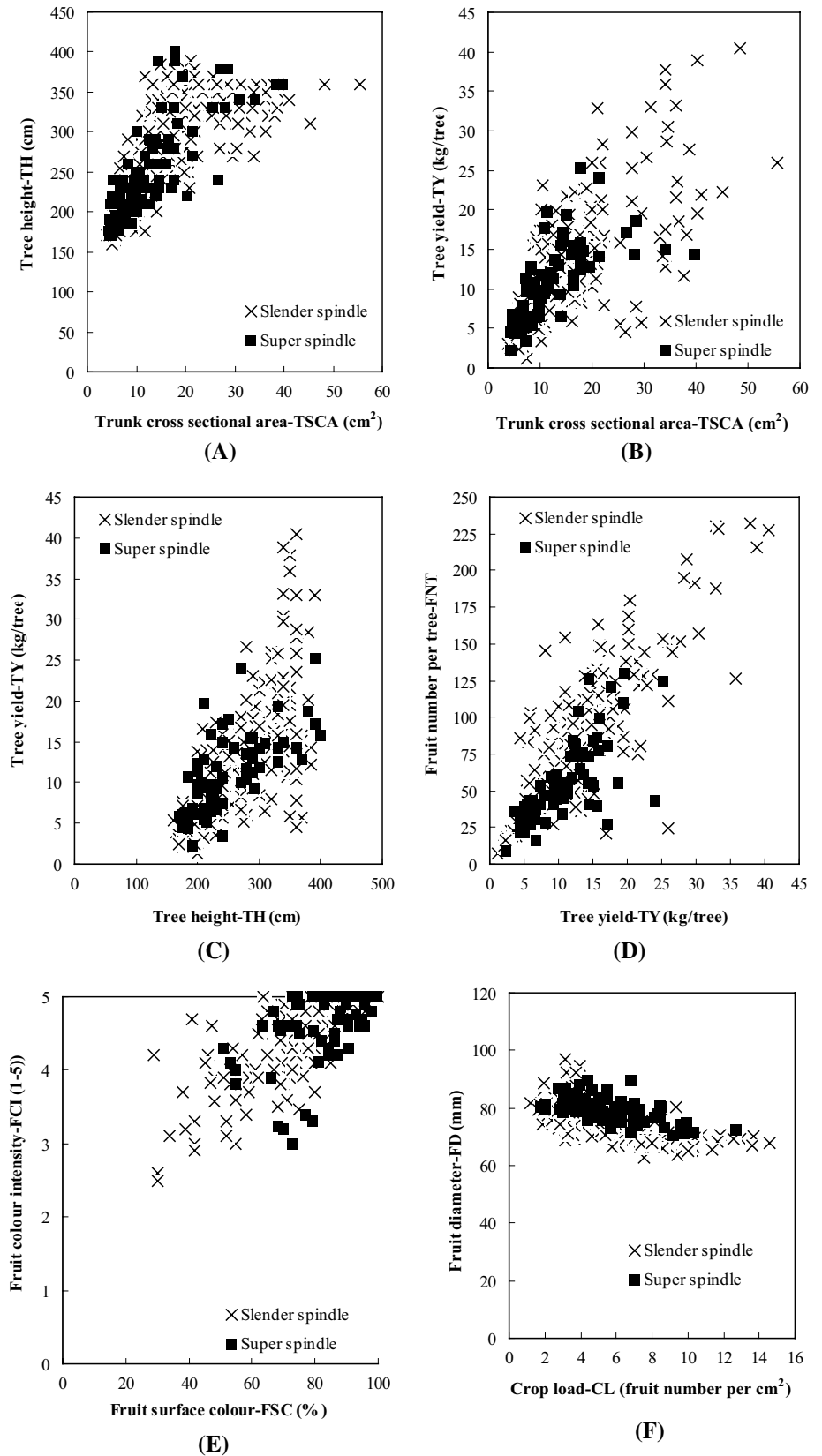


Table 9 Results of Principal Component Analyses prepared for nine tree parameters on thirteen apple cultivars under two training systems

Items	PC1	PC2	PC3	PC4
Eigenvalue	2.98	1.88	1.79	1.15
Proportion of variance (%)	33	21	20	13
Cumulative variance (%)	33	54	74	87
<i>Eigenvectors</i>				
Trunk cross sectional area—TSCA	0.84	-0.30	-0.13	0.23
Tree height—TH	0.79	-0.05	0.04	0.40
Tree yield—TY	0.94	0.13	0.02	0.01
Fruit number per tree—FNT	0.81	0.48	-0.13	0.11
Crop load—CL	0.02	0.91	-0.04	-0.14
Fruit diameter—FD	-0.02	-0.82	0.20	-0.23
Shape index—SI	0.31	0.07	0.09	0.90
Fruit surface colour—FSC	-0.09	-0.16	0.90	0.19
Fruit colour intensity—FCI	-0.01	-0.07	0.94	-0.08

PC: principal component with eigenvalues > 1 were evaluated. Values > 0.350 are considered significant and are highlighted in bold

compared to cultivars trained to super spindle (Table 5) with the exception of trees of ‘Wilton’s Red Jonaprince’ trained to super spindle. This result was in agreement with the study of Ossenbruggen (2012) reporting that this cultivar had strong vigour, especially in the younger age of the trees. This indicates that a more vigorous cultivar planted in denser tree spacing can reach larger trunk thickness than a less vigorous cultivar grown in a larger planting distance, despite the higher root competition in the higher density plantations. In such cases, the space utilization of the cultivar may be more dominant than the tree spaces provided by training systems.

Our study showed that the trunk of the six-year-old trees of ‘Early Red One’ was relatively thin (14.5 cm²), suggesting a low vigour, while the studies of Dennis et al. (1996) and Farina et al. (2009) ranked this cultivar as medium vigour (similar to the standard ‘Red Delicious’). Similar to ‘Early Red One’, the six-year-old trees of ‘Red Cap Valtod (S)’ also showed similar weak trunk thickness (14.8 cm²) in our study; however, a previous study of Guerra et al. (2008) reported that this cultivar has medium vigour such as the spur-type Red Delicious strains. The possible reasons for these different results may be due to that the previous studies evaluated the above cultivars under different climatic and ecological conditions as well as training systems compared to this study.

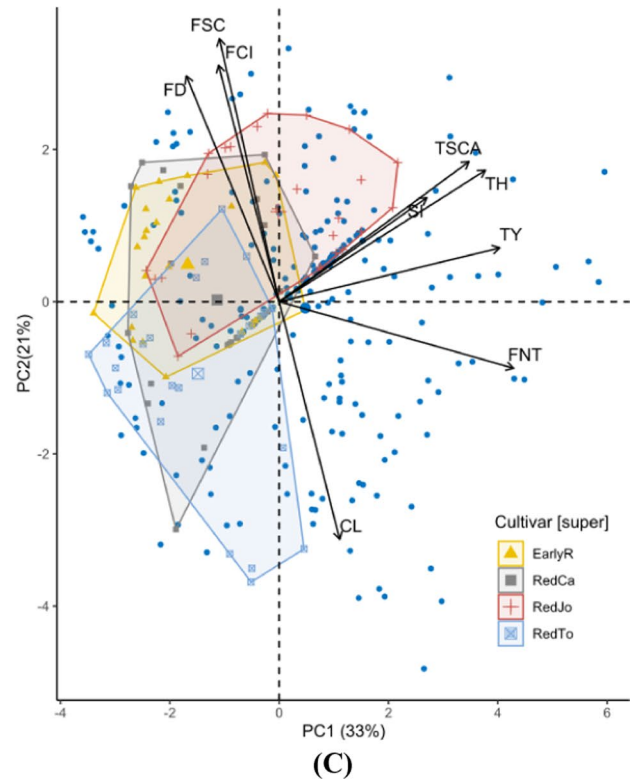
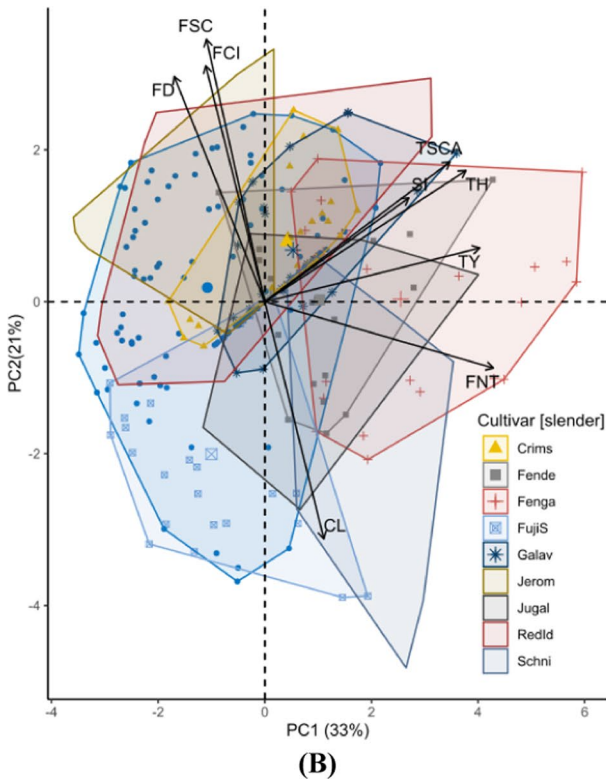
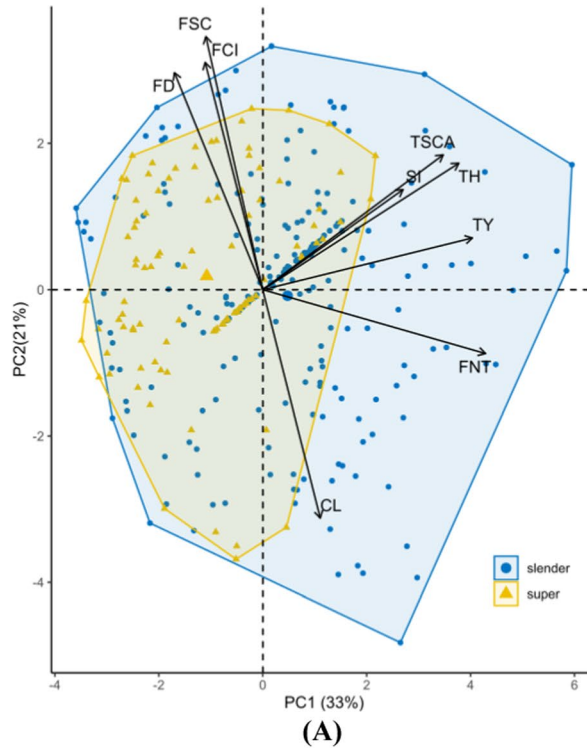
Higher fruit number per tree of the slender spindle system canopy was observed in our study in agreement with the results of the studies of Weber (2001) and Hampson et al. (2002). However, our examinations also showed that the slender spindle canopy with a less vigorous cultivar may also have lower fruit number per tree, which was in agreement with the study of Ezzat et al. (2020). This indicates that

fruit number and TCSA together can equalize the differences of cultivars and training systems; i.e. the lower fruit number of the super spindle trained trees with smaller cropping surface can provide similar or higher crop loads compared to the larger cropping surface of slender spindle trained trees with higher fruit number.

In this study, ‘Gala Schnitzer (S) Schniga’, ‘Gala Decarli-Fendeca’ and ‘Gala Venus Fengal’ reached a crop load of 9.7–12.7 fruit per cm² TCSA on three-year-old trees. A previous study by Stebbins (1989) showed that a crop load between 7 and 13 fruit per cm² TCSA resulted in poor yield for 10 apple cultivars in the following year. In addition, Robinson and Watkins (2003) reported that a crop load above 10 fruit per cm² TCSA considerably reduced fruit diameter and fruit coloration. This result was in agreement with our results of the negative relationship between crop load and fruit diameter, which indicated that the increasing crop load results in a decreasing fruit diameter for most cultivars (Table 8) and for both training systems (Figs. 1 and 2). Robinson and Watkins (2003) also reported that the fruit coloration started to decrease at a crop load of 6 fruit per cm² TCSA. Robinson (2008) recommended a crop load of 6 fruit per cm² TCSA for ‘Gala’ (i.e. 30–50 apples for a three-year-old tree of this study). However, our study indicated that crop loads between 9 and 11 fruit per cm² TCSA were acceptable for the ‘Gala’ mutants, as fruit surface coloration did not decrease considerably. The contradicting results may be due to that the above cultivars were grown in different climatic conditions in this study compared to the previous ones.

Our study clearly showed that the fruit diameter was dependent on the cultivar’s genetic features, which was in agreement with the results of Dallabetta et al. (2014). For example, ‘Gala Schnitzer (S) Schniga’ is classified as a small-fruited cultivar with a fruit size of around 70 mm (Yoon et al. 2020), which was similar to the ranges of fruit diameter of this cultivar (66.3 and 73.5 mm) in this study (Table 7). All cultivars reached the minimum market requirement of 70 mm fruit size (Yoon et al. 2020) by the tree age of 4 years old (Table 7). Cultivars ‘Wilton’s Red Jonaprince’ and ‘Red Idared’ showed a large fruit diameter (around 80 mm), and in 2014, ‘Red Idared’ exceeded the fruit diameter of 90 mm, which can negatively influence harvest packaging and fruit health during storage (Holb et al. 2012).

This study revealed that tree yield had strong relationships with TCSA, height and fruit number per tree for most cultivars (Table 9) in both training systems (Tables 8 and Figs. 1, 2 and 3). Yield values of the investigated cultivars showed medium or high levels in this study (Table 6) compared to previous studies (e.g. Robinson 2008; Kviklys et al. 2013; Reig et al. 2019). On the other hand, in this study, the high yield of ‘Wilton’s Red Jonaprince’ in 2015 (Table 6)



was in agreement with the studies of Kviklys et al. (2013) and Wójcik (2020) who reported an outstanding productivity of this cultivar.

In agreement with previous studies, most cultivars showed a globular shape (the shape index was between 0.85

and 0.90), with the exception of, for example ‘Red Topaz’, which displayed flat fruit (Table 7). In addition, fruit of mutants of ‘Red Delicious’ (‘Jeromine’, ‘Red Cap Valdo (S)’ and ‘Early Red One’) showed flattened shape in trees of 3–4 years old, but later their fruits became globular or

Fig. 3 Biplot diagram of Principal Component Analyses (PCA) prepared on the measured two vegetative (trunk cross sectional area (TCSA) and tree height (TH)) and seven generative parameters (tree yield (TY), fruit number per tree (FNT), crop load (CL), fruit diameter (FD), shape index (SI), fruit surface color (FSC) and fruit color intensity (FCI)) on thirteen apple cultivars (Crims: ‘Crimson Crisp (Co-op 39)’, Fende: ‘Gala Decarli-Fendeca’, Fenga: ‘Gala Venus Fengal’, FujiS: ‘Fuji September Wonder’, Galav: ‘Galaval’, Jerom: ‘Jeromine’, Jugal: ‘Jugala’, RedId: ‘Red Idared’, Schni: ‘Gala Schnitzer (S) Schniga’, EarlyR: ‘Early Red One’, RedCa: ‘Red Cap Valtod (S)’, RedJo: ‘Wilton’s Red Jonaprince’, and RedTo: ‘Red Topaz’) in two training systems (super and slender spindle). A: 95% ellipses were separated for the two training systems, B: 95% ellipses were separated for nine apple cultivars in the slender spindle training system and C: 95% ellipses were separated for four apple cultivars in super spindle training system

slightly elongated (the shape index was between 0.84 and 0.90). This phenomenon corresponds to the results of Bassi et al. (2010) as the fruit shape of the cultivar group of ‘Red Delicious’ can be flattened or globular on young trees, but later fruits become more elongated.

Most cultivars had good surface coloration and fruit color intensity in this study (Table 7). In addition, significant inter-correlations for the two parameters were also revealed by Pearson correlation, regression and principal component analysis (Table 9, Figs. 1, 2 and 3). A previous study by Guerra and Sansavini (2012) showed that mutants of ‘Gala’ reached 100% fruit surface color in the breeding programs; however, our studies showed various fruit surface colorations for mutants of ‘Gala’ (82–90, 84–91, 74–89, 62–76, and 40–68% for ‘Galaval’, ‘Gala Decarli-Fendeca’, ‘Gala Venus Fengal’, ‘Jugala’, and ‘Gala Schnitzer (S) Schniga’, respectively). Several previous studies supported our findings such as (i) Rühmer (2015) who reported 89 and 94% red over-coloration for ‘Gala Venus Fengal’ and ‘Gala Decarli-Fendeca’, respectively; (ii) Montagnon (2014) who found 94% fruit surface color for ‘Galaval’; (iii) Guerra and Sansavini (2012) who reported relatively low skin red colour for ‘Jugala’; and (iv) the study of Bassi et al. (2012) that reported low red coloration (50–80%) for ‘Gala Schnitzer (S) Schniga’. Therefore, Guerra et al. (2013) suggested that harvest of ‘Gala Schnitzer (S) Schniga’ has to be performed in 2–3 picks due to the slow ripening and coloration. In the case of ‘Wilton’s Red Jonaprince’, Kviklys et al. (2013) found the best red skin coloration of ‘Wilton’s Red Jonaprince’ (99%) among different ‘Jonagold’ clones; however, this result was partially contradicting with our results as the coloration in our study ranged from 79 to 88%. In addition, ‘Crimson Crisp’ showed 70–91% red skin color in this study, while colorations varied (95–100 and 77–87%) in the previous study of Bassi et al. (2012). Our results on skin coloration of ‘Red Topaz’ showed 59–85% surface color (Table 7) while Tupy and Louda (2008) reported 100% and Ilie and Stanica (2012) reported 75–100% red skin colorations of this

cultivar. The different coloration of the cultivars may be due to differences in tree age, crop load and climatic conditions of our study compared to the previous ones.

5 Conclusions

This study revealed various vegetative and generative properties of the evaluated cultivars in 2- to 6-year-old trees and indicated strong associations among these properties under high density training systems under natural environmental conditions in Central Europe. Our results were partly contradictory with previous studies, which indicated the importance of cultivar testing under different climatic conditions, as the results of this testing largely influence the cultivar choice of the growers for designing new plantations. In this study, the overall vegetative and generative performances can be considered as best for ‘Galaval’, ‘Gala Decarli-Fendeca’, ‘Crimson Crisp’, ‘Wilton’s Red Jonaprince’ and ‘Red Idared’ grown under central European climatic conditions. These cultivars are advised to growers/advisors for establishing new apple orchards under climatic conditions similar to central Europe.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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Authors and Affiliations

Ádám Csihon¹ · István Gonda¹ · Szilárd Szabó² · Imre J. Holb^{1,3} 

¹ Institute of Horticulture, University of Debrecen, Debrecen 4032, Hungary

² Department of Physical Geography and Geoinformatics, University of Debrecen, Debrecen 4032, Hungary

³ Plant Protection Institute, Centre for Agricultural Research, Eötvös Loránd Research Network, ELKH, Budapest 1022, Hungary