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SUITABILITY OF PLUM AND PRUNE CULTIVARS, GROWN IN A HIGH DENSITY PLANTING SYSTEM, FOR MECHANICAL HARVESTING WITH A CANOPY CONTACT, STRADDLE HARVESTER

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ABSTRACT

The relation of hand-harvesting cost in plum and prune production to the total costs amounts to 25-40%. Mechanical harvesting makes it possible to cut drastically both the harvesting and total costs. To test the suitability of plum and prune species to be mechanically harvested, an experimental grove (area 0.8 ha) was established in 2008. Three plum cultivars and one prune cultivar grafted on semi-dwarf and vigorous rootstocks were planted at high density (1250; 1666; 2500 trees$\cdot$ha^{-1}). During the span of full yielding (2012-2014), fruits were harvested mechanically with a canopy contact, straddle harvester in continuous motion, designed at the Institute of Horticulture in Skierniewice, to harvest tart cherry, and later adapted to harvesting plums and prunes. Trees grafted on semi-dwarf rootstock (‘Wangenheim Prune’) appeared to be more suitable for mechanical harvesting than strong-growing trees grafted on *Prunus cerasifera* clone ‘Myrobalan’. Cumulative yield per ha (years 2012-2014) was the highest at the highest planting density. Trees grafted on the semi-dwarf rootstock had a higher productivity index than trees grafted on the vigorous rootstock. There was no significant difference in fruit quality related to planting distance. Mechanical harvesting was nearly 40 times more efficient than hand picking. The efficiency of mechanical harvest was from 85% to 90%. Over 5% of fruits were lost on the ground and from 1 to 5% of fruits were left on the tree. Up to 18% of the plums and no more than 10% of the prunes harvested mechanically showed some damage. They can be fully acceptable for processing, for up to 10 days, providing the potential deterioration processes are inhibited by cold storage. The large-fruited cultivars seem to be more susceptible to bruising than the small-fruited ones. For the latter, the share of marketable quality fruits within the mechanically harvested crop amounted to about 80%, which could be a good prognostic justifying further trials on the prune harvester.

Key words: plums (*Prunus domestica* L.), mechanical harvesting, yielding, fruit quality

INTRODUCTION

Plums and prunes in Poland belong to the few leading fruit species with a yearly production of around 110 000 tons. Most of the fruit is processed into jams, compotes, used in baking industry or as frozen product. In the total cost of fruit production, the cost of fruit harvesting is estimated at 25 to 40%. Reducing the labor cost of harvesting is presently very important, not only in Poland but in Europe (Sarig 2012).

In earlier experimental work (Mika et al. 2011b), mechanical harvesting of sour (tart) cherries was solved by a straddle, canopy contact, harvester working in continuous motion. The harvester, assisted by 4 workers, could replace over 100 hand pickers on a tart cherry plantation. Mechanical fruit harvesting in continuous motion requires the plantation to be adapted to such technology (Mika & Buler 2011; Sarig 2012). To adapt plum and prune trees to mechanical fruit harvesting, we took advantage of our results with sour cherries grown for

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such purpose (Mika et al. 2011a). Plum and prune trees were densely planted in rows to form a continuous wall (hedgerow). Such a training system, with trees of limited width and height, was also suggested for olive trees designed for mechanical fruit harvesting (Ferguson et al. 2012). The trees were trained to the leader form with flexible lateral branches that were able to pass into the interior part of the harvesting machine. The planting system was somewhat similar to that of olive trees for mechanical harvesting described by Morales-Sillero et al. (2014), but the trees were planted at high density. Trees were trained by winter, summer and renewal pruning; tree training was performed in winter and summer, and renewal pruning was also applied. Training to a slender leader, introduced by Mika et al. (2012), was performed. In early June, 2 or 3 top shoots competing with the leader were removed, which resulted in a fast growth of the leader with numerous laterals. From the third year onward, renewal pruning was applied, introduced in Poland by Czynczyk et al. (1976). This pruning system involves cutting out branches when they attain the age of 3 years and replacing them with one-year-old shoots. The renewal pruning was supplemented with light thinning of small branches. As a result of such pruning, canopy width was kept to a constant spread of 2.0 m.

In Poland, most plum and prune cultivars are grafted on Myrobalan seedlings (*Prunus divaricata* Led., clone ‘Myrobalan’) and about 20% on seedlings of a selected clone of ‘Wangenheim Prune’. Plum trees grafted on Myrobalan seedlings are rather strong growing, like those on Myrobalan C. Such trees are planted in standard orchards at 4 × 3 to 5 × 5 m and trained to a regulated leader tree. Cultivars grafted on ‘Wangenheim Prune’ are semi-dwarf, tolerant to arid soils common in Poland, and very productive (Sitarek et al. 2001). In Poland, they are usually spaced at 4 × 3 m. In Germany, Zahn (1994) and Brunner (1990) introduced a central leader spindle and free spindle (without shoot bending) for dwarf and semi-dwarf densely planted plums and prunes. These systems, tested in Belgium (Wustenberghs & Keulemans 1996) with 825 and 1250 trees per ha, appeared to be economically efficient in yielding and harvesting.

The goal of the experiment was to develop an orchard model of plum cultivars bearing large fruit and small fruit, and a prune cultivar bearing small fruit, suitable for mechanical harvesting. The straddle, canopy contact, self-propelled harvester working in continuous motion, originally designed for sour cherries, but adapted to harvesting plums and prunes, was used.

MATERIALS AND METHODS

Plant material characteristics

Three plum cultivars (*Prunus domestica*): ‘Cacanska Lepotica’, ‘Jojo’, ‘Valjevka’, and one prune cultivar ‘Sweet Prune’ (*Prunealiana*), were planted in the spring of 2008 at the Research Institute of Horticulture, Skierniewice, Poland (longitude 51°57’ N, latitude 20°08’ E, altitude 120 m), in a sandy-loam, deep soil with pH 5.5. This area is characterized by a Central European climate with 507 mm of rainfall yearly and 489 mm of evapotranspiration during the growing season. The mean temperature of the coldest month of January is −3.1 °C, and the mean temperature of the warmest month of July is 18.1 °C. ‘Cacanska Lepotica’ and ‘Jojo’ produce large fruits (40-50 g) and are mainly used in Poland as dessert plums, whereas ‘Valjevka’ and ‘Sweet prune’ bear smaller fruits, not exceeding 35 g, and are excellent for processing.

Experimental orchard management

To facilitate the work of a straddle harvester working in continuous motion, semi-dwarf trees (‘Cacanska Lepotica’ and ‘Jojo’) grafted on the ‘Wangenheim Prune’ rootstock were spaced 4 m between rows and 1.0 or 1.5 m in the row (2500, 1666 trees$\cdot$ha^{-1}). Cultivars ‘Valjevka’ and ‘Sweet Prune’, grafted on the vigorous rootstock ‘Myrobalan’ (*Prunus cerasifera*) were spaced 4 m between rows and 1.5 or 2.0 m in the row (1666, 1250 trees$\cdot$ha^{-1}). In the second year after planting, the inter-rows were grassed down, with frequent grass mowing in conjunction with the maintenance of 1.5-m-wide herbicide strips along the rows. Trees were irrigated periodically, only in dry periods, from May to September. The mean dose of water in summer time was 200 mm, estimated as rainfall.

The irrigation system consisted of two compensating lines per row supplying 2.5 $l \cdot h^{-1}$ per tree. Trees were fertilized according to soil analyses. Due to the high mineral content in the soil, fertilization was very low. At the start, the trees received 80 kg K per ha, then only 20 kg N per ha yearly. Eight to ten sprayings were essential to control pests and diseases.

Training and pruning the grove designed for mechanical harvesting

The experiment was conducted in a randomized block design with four replications. The area of the experimental grove was 0.8 ha. Each cultivar was planted in two rows, each 200 m long. In each row, mechanically or manually harvested trees were arranged in four plots with 25, 35, or 50 trees in a plot, depending on the planting distance. The plots (hand and mechanical harvesting) were managed in the same way. A new way of tree training and pruning was applied. The planted trees had long leaders (up to 2 m, as measured from the ground) and a few weak laterals. The leaders (height up to 2 m from the ground) were slightly headed to 1.7 m and the lateral shoots lightly pruned after tree planting. In early June, for a span of three years, 2 or 3 top shoots competing with the leader were removed in order to stimulate the lower part of the leader to branching. This treatment resulted in the development of many short, lateral shoots along the leader. In the third year after planting, the trees were suitable for mechanical harvesting with a straddle harvester working in continuous motion. The harvester required trees with a straight leader not exceeding a height of 2.8 m and short, flexible branches. To assure such a canopy structure, renewal pruning introduced in Poland by Czynczyk et al. (1976) was implemented from the third year onwards. The renewal pruning that was implemented from the third year onwards consisted in the removal of 3 or 5 of the oldest, large branches and leaving a stump at the leader. Stumps 50 to 200 mm long assured sprouting of new shoots necessary for tree renewal in subsequent years.

Evaluation of trees characteristics prepared to mechanical harvesting

Renewal pruning, as performed in this trial, is possible when certain fruit species have the ability to set fruit buds on one, two and three-year-old wood. This phenomenon was studied for three years to prove that such an ability would be long lasting. For this purpose, two branches were selected, on six trees, from two sides of the tree canopy, to record cluster fruit buds before blooming, and the number of fruit in July. Every year, measurements of the circumstance of the tree trunk were taken 0.3 m above the ground and used to calculate the trunk cross-section area (TCSA). The yield was recorded as the total yield from all the trees on the plot and recalculated as per the tree.

Mechanical harvesting

Three harvesting trials were performed during the period of 2012-2014, after the trees had come into full bearing. Each cultivar was harvested in one day. A canopy contact, straddle fruit harvester in continuous motion, in the form of a diesel-hydraulic driven combine, with a wide range of velocity and shaking frequency adjustment, was used. Technical data of the harvester was as follows: length 8.4 m in working position, width 4.0 m, height 3.9 m, clearance 2.8 m, power – 50 kW, travel velocity 0.6 – 10 $km \cdot h^{-1}$, number of shakers – 4, shaking frequency 0-20 Hz, shaker fingers stroke 65-90 mm, crew 3-5 people. The harvesting was carried out at a travel velocity of 0.8 $km \cdot h^{-1}$ with a shaking frequency of 6 Hz for cultivars with large-size fruits and 8 Hz for cultivars with small-size fruits. The shaker finger stroke was 90 mm.

Description of fruit quality prior to harvest

On the day of the harvest, the quality of plum and prune fruit was characterized. For each cultivar, four samples of 25 fruits with stems each were cut off the trees. First, the force (N) needed to detach fruit from stem was measured with a digital dynamometer. Then, the mean weight of a single fruit was recorded (± 0,01 g). Fruit firmness (N) was measured with an Instron 4303 machine, and expressed as the force needed to puncture the fruit with a 3.5 mm dia. probe moving at a speed of 50 $mm \cdot min^{-1}$. Also, the soluble solids, titratable acidity and total anthocyanin content were determined for each combination.

Indices describing harvest effectiveness

Directly after harvest, the quantities of the fruit collected, the fruit remaining on the tree and that lost on the ground, fruit yield per plot, and harvesting efficiency in $t \cdot h^{-1}$ and $ha \cdot h^{-1}$ were calculated. To estimate the consequence of the harvester moving along a tree row, the number of damaged shoots (broken or with the bark rubbed off) was recorded. The average time of hand harvest was determined by measuring the time taken by 4 people to pick all the fruit from each replication.

Fruit quality characteristics after harvest

To compare the quality of mechanically versus hand-harvested fruit, a 2 kg sample of the fruit in two random repetitions was taken from each combination. Each fruit sample was first manually sorted to distinguish the percentage of fruits with the stem and without the stem (the mass percentage). Then the fruits were sorted again to determine the percentage of fruit of marketable quality as dessert fruit. Within the sub-standard crop, the fruits with signs of mechanical damage, fruits injured by fungi and insects, as well as the unripe and over-ripe ones were separated.

As well as determination of fruit quality on the day of the harvest, the suitability of mechanically harvested yield for storage was also compared with the quality of handpicked fruits. For the storability test, only wholesome fruits without any visible defects were taken. Both kinds of samples consisted of 20 fruits, which were stored for 5 days at a temperature of 18 °C, and for 10 days in a cold store (0 °C). The quality of the fruit was checked twice, first after 1 day of storage and then after the end of the storage test. The sensory quality was evaluated employing a consensus method carried out by a 3 person team. Sensory assessment included traits describing the appearance of the fruit and the taste and texture, with consumption quality determined by the results of the aforementioned characteristics. For each quality attribute, a 5-point scale was established with certain end point definitions.

Statistical analysis

The results were statistically elaborated using an analysis of variance, followed by means separation using Duncan multiple-range t-test at $p = 0.05$.

RESULTS

Influence of training and pruning, needed to enable mechanical harvest, on young tree growth and fruit bud setting

The growth of trees in the seventh year (2014), expressed by trunk cross-sectional area (TCSA), is presented in Table 4. Significant differences in TCSA between the trees grown on different rootstocks and between the trees grown at different spacings in the row are present. 'Myrobalan' trees had a TSCA twice as large, while the trees spaced further apart in the row had a slightly larger TSCA, in comparison with other trees.

Renewal pruning can be performed when trees set fruit buds on young wood. This phenomenon was studied over 3 years. Table 1 shows the ability of young wood to set fruit buds in fully-grown trees from the fifth year after planting. Most of the cultivars were able to set about 80% of fruit bud clusters on one-year-old and two-year-old wood, although many differences in this ability were found among the cultivars. The rest of fruit buds (nearly 20%) was set on three-year-old wood. The percentage of fruit on one-year-old and two-year-old wood was similar to the percentage of flower bud clusters, that is, around 90% (Table 2). These results indicate that the trees subjected to renewal pruning produce enough fruiting wood and the pruning method should not have an adverse effect on tree yielding. Bare wood observed on trees subjected to traditional regulated pruning was not observed in this experiment.

Effect of planting density and rootstock on tree productivity

The first crop of fruit (1-3 $kg \cdot tree^{-1}$) was obtained in the second year from planting. In the fifth year (2012), trees delivered a sufficient crop to be harvested by the combine harvester and to compare with hand picking. In the span 2012-2014, the crop of plums and prunes revealed considerable fluctuation. Although the estimated mean crop per tree/year was around 15 kg (Table 3), significant differences were found in cumulative yield between cultivar/rootstock combinations and planting densities (Table 4). Irrespective of cultivar and rootstock, the higher planting density (1.0 and 1.5 m in the row) depressed the cumulative yield per tree. The substantial drop in yields in 2014, noted for the trees grafted on the 'Myrobalan' rootstock, was connected with their excessive canopy spread, which had to be restricted by pruning. The cultivars 'Cacanska Lepotica' and 'Jojo' grafted on 'Wangenheim Prune', spaced 1.0 and 1.5 m apart, appeared to be the most productive. The mean yield calculated per ha/year was within the range 20-30 tons.

Table 1. Percentage of fruit bud clusters on young wood in the 5th to 7th year from planting (2012-2014)

Cultivar/rootstock Treatment	2012			2013			2014		
	Shoot age			Shoot age			Shoot age		
	1-year old	2-year old	3-year old	1-year old	2-year old	3-year old	1-year old	2-year old	3-year old
C. Lepotica/W.P.*	48.1	41.8	10.1	52.4	46.4	1.2	69.5	29.4	1.1
Jojo/W.P.	37.1	57.4	5.5	51.2	42.4	6.4	42.0	52.0	6.0
Valjevka/M.**	26.2	69.3	4.5	45.1	43.2	11.7	40.4	44.3	15.3
Sweet Prune/M.	41.1	57.6	1.3	54.5	42.0	3.5	49.1	42.4	8.5

*W.P. – Wangenheim Prune rootstock
**M. – Myrobalan rootstock

Table 2. Percentage of fruits on young wood in the 5th to 7th year from planting (2012-2014)

Cultivar/rootstock Treatment	2012			2013			2014		
	Shoot age			Shoot age			Shoot age		
	1-year old	2-year old	3-year old	1-year old	2-year old	3-year old	1-year old	2-year old	3-year old
C. Lepotica/W.P.*	37.7	61.5	0.8	45.8	53.6	0.6	55.7	42.4	1.9
Jojo/W.P.	28.3	69.6	2.1	40.0	58.7	1.3	6.1	93.9	0.0
Valjevka/M.**	25.0	74.0	1.0	40.3	53.3	6.4	7.9	74.9	17.2
Sweet Prune/M.	49.9	49.8	0.3	56.6	42.4	1.0	47.4	46.4	6.2

See: Table 1

Table 3. Effect of cultivar/rootstock and tree spacing on hand-picked yield (kg·tree^{-1}) (2012-2014)

Cultivar/rootstock	2012		2013		2014	
	4 × 1.0 m	**4 × 1.5 m**	**4 × 1.0 m**	**4 × 1.5 m**	**4 × 1.0 m**	**4 × 1.5 m**
C. Lepotica/W.P.**	10.8 a*	14.6 ab	18.9 b	19.8 b	15.6 c	23.7 d
Jojo/W.P.	9.8 a	17.4 b	12.5 a	13.5 a	7.4 a	10.7 b
	4 × 1.5 m	**4 × 2.0 m**	**4 × 1.5 m**	**4 × 2.0 m**	**4 × 1.5 m**	**4 × 2.0 m**
Valjevka/M.***	11.0 a	11.8 a	23.8 a	30.4 b	5.9 c	8.2 d
Sweet Prune/M.	9.6 a	12.9 a	27.4 ab	28.5 ab	3.6 a	4.6 b

*Different letters indicate significant difference at $p = 0.05$, separately for years and rootstocks, according to DMRT
See: Table 1

Table 4. Effect of cultivar/rootstock and tree spacing on cumulative yield, TCSA and productivity index

Cultivar/rootstock	Cumulative yield 2012-2014 (kg·tree^{-1})		Cumulative yield 2012-2014 (t·ha^{-1})		TCSA**** 2014 (cm^2)		Productivity index 2014 (kg·cm^{-2})	
	4 × 1.0 m	**4 × 1.5 m**	**4 × 1.0 m**	**4 × 1.5 m**	**4 × 1.0 m**	**4 × 1.5 m**	**4 × 1.0 m**	**4 × 1.5 m**
C. Lepotica/W.P.**	45.3 b*	58.1 c	113.3 c	96.8 b	32.5 a	44.4 a	1.4 b	1.3 b
Jojo/W.P.	29.7 a	41.6 b	74.3 a	69.3 a	34.3 a	58.1 b	0.9 a	0.7 a
	4 × 1.5 m	**4 × 2.0 m**	**4 × 1.5 m**	**4 × 2.0 m**	**4 × 1.5 m**	**4 × 2.0 m**	**4 × 1.5 m**	**4 × 2.0 m**
Valjevka/M.***	40.7 a	50.4 b	67.8 b	63.0 b	75.2 a	97.7 c	0.5 a	0.5 a
Sweet Prune/M.	40.6 a	46.0 a	67.6 b	57.5 a	81.2 ab	87.7 b	0.5 a	0.5 a

*Different letters indicate significant difference at $p = 0.05$, separately for rootstocks, according to DMRT
**W.P. – Wangenheim Prune rootstock; ***M. – Myrobalan rootstock; ****TCSA – Trunk cross-sectional area

The productivity index (Table 4) of the semi-dwarf trees was, on average, more than twice as high as that of the trees grafted on the strong-growing rootstock.

Fruit quality characteristics at harvest

Fruits were harvested when they had reached the required pigmentation and a certain level of detachment force, which was regularly monitored prior to harvest by several tests. The optimal detachment force for large-fruited cultivars is considered to be a value in the range of 6-8 N, while for small-fruited cultivars it is 5-6 N. Unfortunately, not all the fruits on a tree ripen at the same time. Usually, when about 90% of the fruits had the optimum detachment force for harvesting, the rest showed it to be too weak or too strong. The mean values of the detachment force at harvest time as well as the other quality attributes of fruit picked in consecutive years are presented in Table 5. Generally, the degree of ripeness of a particular cultivar, taken as a resultant of different quality characteristics, can be considered within the span of the experiment as repeatable enough.

Harvest effectiveness

Table 6 presents the efficiency of mechanical harvesting of the four cultivars over their full fruit-bearing span (2012-2014). The efficiency of mechanical harvesting with the machine assisted by 4 workers depended mostly on fruit yield. At a yield of 25-35 $t \cdot ha^{-1}$, the obtained efficiency was around 7 $t \cdot h^{-1}$, whereas at yields of 10-15 $t \cdot ha^{-1}$, the efficiency was 2.5-3.5 $t \cdot h^{-1}$. The harvester was able to harvest 0.25 $ha \cdot h^{-1}$ in those cases where fruits were collected to large bins, and empty bins were supplied to the machine in time. The efficiency of hand picking relied mostly on the size of fruit, but also on the number of fruits on the tree. Large fruits and abundant crop are the main factors determining high efficiency of hand picking. Comparing the efficiency of harvesting by 4 workers, they were able to harvest 0.10-0.16 $t \cdot h^{-1}$. Hand picking was nearly 40 times less efficient than mechanical harvesting.

Table 5. Fruit quality prior to harvest. Means for seasons 2012-2014

Cultivar/rootstock	Detachment force (N)	Mean fruit weight (g)	Firmness (N)	Total soluble solids (%)	Acidity (%)	Total anthocyanin content ($mg \cdot 100\ g^{-1}$)
2012						
Cacanska Lepotica/W.P.**	9.41 c*	39.1 c	8.7 b	14.9 a	1.25 b	20.8 b
Jojo/W.P.	7.41 b	26.9 b	8.6 b	14.9 a	1.36 c	17.4 a
Valjevka/M.***	8.01 b	29.4 bc	9.8 c	21.8 b	1.19 b	39.9 c
Sweet Prune/M	5.26 a	19.1 a	7.3 a	22.9 b	0.63 a	21.2 b
2013						
Cacanska Lepotica/W.P.	10.59 c	44.9 d	8.9 c	14.1 a	1.11 c	14.7 a
Jojo/W.P.	6.69 b	37.5 c	8.7 c	15.1 b	1.27 d	17.1 b
Valjevka/M.	6.44 b	28.1 b	7.6 b	16.6 c	0.93 b	31.0 c
Sweet Prune/M.	4.61 a	18.0 a	4.6 a	17.0 c	0.59 a	14.1 a
2014						
Cacanska Lepotica/W.P.	9.08 c	46.4 d	8.7 b	13.6 a	1.05 c	13.0 a
Jojo/W.P.	6.19 b	55.3 c	6.2 a	15.0 a	0.87 b	28.7 b
Valjevka/M.	3.21 a	35.6 b	6.4 a	19.0 b	0.87 b	39.5 c
Sweet Prune/M.	5.05 b	21.1 a	6.2 a	22.4 c	0.62 a	16.3 a

*Different letters indicate significant difference among cultivars, separately for years, at p = 0.05 according to DMRT
**W.P. – Wangenheim Prune rootstock
***M. – Myrobalan rootstock

Table 6. Efficiency of mechanical harvesting compared with hand picking by 4 workers employed in 2012-2014

Cultivar/rootstock	Estimated yield ($t \cdot ha^{-1}$)		Efficiency ($t \cdot h^{-1}$)		Efficiency ($ha \cdot h^{-1}$)	Efficiency ($trees \cdot h^{-1}$)
	Mechanical harvesting	Hand picking	Mechanical harvesting	Hand picking	Mechanical harvesting	Hand picking
2012						
C. Lepotica/W.P.*	24.81	30.30	3.47	0.14	0.23	10
Jojo/W.P.	38.30	44.00	6.89	0.16	0.18	11
Valjevka/M.**	15.65	16.50	3.36	0.12	0.29	10
Sweet Prune/M.	13.83	10.80	3.48	0.10	0.25	11
2013						
C. Lepotica/W.P.	35.73	40.00	6.48	0.15	0.25	8
Jojo/W.P.	48.25	53.00	7.40	0.16	0.22	12
Valjevka/M.	26.85	37.70	6.77	0.12	0.25	5
Sweet Prune/M.	35.00	41.00	6.79	0.12	0.23	4
2014						
C. Lepotica/W.P.	33.94	39.00	7.33	0.15	0.22	8
Jojo/W.P.	15.54	19.00	2.46	0.12	0.29	13
Valjevka/M.	9.92	10.00	2.86	0.10	0.29	14
Sweet Prune/M.	6.52	6.00	2.40	0.10	0.22	25

See: Table 1

Table 7. Efficiency of fruit collection in mechanical harvesting in 2012-2014

Cultivar and date of harvesting	Fruits collected (kg/%)	Fruits remaining on the tree (kg/%)	Fruits lost on the ground (kg/%)	Total yield (kg/%)	Number of trees harvested	Mean yield ($kg \cdot tree^{-1}$)
2012						
C. Lepotica/W.P.* 02.08.	474.0/90.4	6.9/1.3	43.2/8.3	524.1/100.0	29***	18.1
Jojo/W.P. 23.08.	3063.9/90.7	70.5/2.1	241.9/7.2	3376.3/100.0	169	20.0
Valjevka/M.** 03.09.	932.0/91.1	36.2/3.5	55.2/5.4	1023.3/100.0	117	8.8
Sweet Prune/M. 17.09.	1106.0/86.4	72.1/5.6	103.1/8.0	1281.2/100.0	119	10.8
2013						
C. Lepotica/W.P. 12.08.	2058.0/93.2	8.4/0.4	141.1/6.4	2207.5/100.0	168	13.1
Jojo/W.P. 05.09.	2740.0/87.0	184.9/5.9	225.3/7.1	3150.2/100.0	169	18.6
Valjevka/M. 10.09.	2148.0/89.1	56.2/2.3	208.1/8.6	2412.3/100.0	119	20.3
Sweet Prune/M. 25.09.	2320.0/88.1	165.5/5.2	177.5/6.7	2634.0/100.0	119	22.1
2014						
C. Lepotica/W.P. 11.08.	2715.3/90.0	39.0/1.3	263.8/8.7	3018.0/100.0	168	18.0
Jojo/W.P. 08.09.	683.0/84.2	0.7/0.1	127.0/15.7	811.1/100.0	169	4.8
Valjevka/M. 05.09.	793.2/92.0	0.0/0.0	69.4/8.0	862.6/100.0	119	7.3
Sweet Prune/M. 18.09.	701.4/95.9	0.0/0.0	30.0/4.1	731.4/100.0	204	3.6

*W.P. – Wangenheim Prune rootstock; **M. – Myrobalan rootstock; *** – Only limited number of trees came into bearing

Table 8. Quality of fruit harvested with a machine harvester (M) compared to the quality of hand-picked fruit (H)

Cultivar		Stem presence			Quality traits			
		Fruits without stem (%)	Fruits with stem (%)	Fruits of marketable quality (%)	Mechanically damaged fruits (%)	Rotten and pest damaged fruits (%)	Over ripened fruits (%)	Unripened fruits (%)
2012								
Cacanska Lepotica	M	40.1 a*	59.9 d	56.4 a	12.7 d	19.6 d	2.2 b	9.1 c
	H	66.0 c	34.0 c	86.0 c	4.9 b	7.5 b	0.0	1.6 a
Jojo	M	52.4 b	47.6 d	49.1 a	6.5 bc	8.2 b	4.2 c	10.0 c
	H	76.8 d	23.2 b	69.2 b	9.0 cd	13.9 c	3.0 b	3.1 b
Valjevka	M	56.5 b	43.5 cd	86.2 c	7.8 c	3.9 a	2.1 b	0.0
	H	64.6 c	36.5 c	88.2 c	0.0	8.7 b	3.1 b	0.0
Sweet Prune	M	66.0 c	34.0 c	82.0 c	8.0 c	8.7 b	1.3 a	0.0
	H	88.7 d	11.3 a	88.9 c	0.9 a	8.6 b	1.6 ab	0.0
2013								
Cacanska Lepotica	M	33.4 a	66.6 c	54.4 b	15.2 d	8.8 b	10.9 c	10.7 cd
	H	72.7 bc	27.3 b	68.3 c	0.0	16.2 c	6.3 b	9.2 c
Jojo	M	67.3 b	32.7 b	48.6 a	12.4 c	19.5 c	0.0	3.2 b
	H	69.4 b	30.6 b	45.0 a	20.1 e	30.7 d	0.0	4.2 b
Valjevka	M	66.7 b	33.3 b	70.4 c	10.1 c	5.1 ab	1.4 a	13.0 d
	H	76.5 c	23.5 b	81.4 cd	0.6 a	6.1 b	0.0	12.0 d
Sweet Prune	M	78.3 c	21.7 b	90.7 d	2.2 b	7.1 b	0.0	0.1 a
	H	97.5 d	2.5 a	94.2 d	3.1 b	2.7 a	0.0	0.0
2014								
Cacanska Lepotica	M	44.9 a	55.1 c	58.5 a	18.6 d	7.0 c	7.6 c	8.3 c
	H	64.6 b	35.4 b	77.7 b	2.2 ab	8.0 c	5.7 b	6.7 c
Jojo	M	40.3 a	59.7 c	86.9 b	6.1 c	2.2 ab	4.8 b	0.0
	H	67.8 b	32.5 b	95.6 c	0.8 a	1.9 a	1.7 a	0.0
Valjevka	M	82.0 c	18.0 a	81.7 b	3.5 b	0.0	13.4 d	1.4 a
	H	78.0 c	22.0 ab	89.0 bc	0.0	0.0	8.0 c	3.0 b
Sweet Prune	M	61.4 b	38.6 b	79.4 b	2.5 b	3.2 b	14.0 d	0.9 a
	H	88.6 d	11.4 a	93.4 c	0.0	0.0	7.6 c	0.0

*Different letters indicate significant difference for each trait, separately for years, at p = 0.05 according to DMRT

The efficiency of fruit collection by the combine-harvester is presented in Table 7. It was difficult to achieve fruit collection efficiency of more than 85-90%, mainly because of the incidence of fruit drop when the harvester initially touched the tree. At that very moment, 5 to 8% of the fruit fell to the ground. This disadvantage resulted from summer shoot growth. In the spring, all strong-growing shoots were removed from the tree canopy and the weaker ones were left for fruiting. By harvesting time, some fruiting wood had become thick and stiff and extended with the summer growth. They were interfering with the harvester body, causing the fruit to drop. Some fruits were also lost when crates or bins were being filled. The amount of fruit left on the tree after the passage of the harvester varied at 1-5%. That amount could be reduced by supplementary pruning in summer and careful matching of the harvesting machine to work.

Impact of mechanical harvesting on yield quality

The quality of the fruit harvested with the harvester as compared with that of hand-picked fruit revealed some interesting differences (Table 8). The percentage of fruit retaining the stem was higher in mechanical harvesting compared with hand picking. This is not an important problem in the case of industrial fruit because stems are easily removed. In the case of dessert plums, there can be a different preference depending on the market. Some markets prefer fruit with the stem, others without it.

As was expected, the percentage of mechanically damaged fruits was generally higher in the case of machine harvest. However, for the cultivar 'Jojo' in 2012 and 2013 the tendency was opposite, which was probably a consequence of strong fungal and microbial infestation (Table 8). A similar problem, connected with ineffective tree protection against pests and diseases, occurred for 'Cacanska Lepotica', which resulted in substantial decreases in the share of marketable-quality fruit, even below 50%.

Regardless of the problem with tree microbial infestation, as well as with ripening diversity, the large-fruited cultivars seem to be more susceptible to bruising than the small-fruited ones. In the case of the former, the share of mechanically injured fruit within machine harvested fruits varied between 6.1 and 18.6%, while for the latter it was clearly lower and amounted to from 2.2 to 10.1% (Table 8). For both investigated small-fruited cultivars, the share of marketable quality fruits within the mechanically harvested crop was pretty high and amounted to about 80% (the only exception was 'Valjevka' in 2013, with 70.4% fruits of standard quality). In the case of these cultivars, the hand operated harvest impacted the increase in the share of marketable quality fruits by from 2 up to 12%, but the differences were not always significant, which should be a good prognostic justifying further trials on the prune harvester.

Suitability of mechanically harvested fruit for storage

As was described above, the differences between the mechanically and handpicked crop depended on the years and cultivars. In general, just after harvesting, the bruising defects were slightly visible. However, the contact of the fruit with the shaking fingers, and then with the harvester's catching system led to the disturbance of the blue wax on the skin. The noticeable decrease in the uniformity of the plum wax outer layer tended to influence the visual fruit attractiveness evaluated on the next day after harvest (Table 9). Although the differences were not statistically significant, the tendency was repeated irrespective of cultivar and storage conditions. Presumably, this was also the reason for quicker fruit flash fading, firmness losses, as well as the diminishing of acid taste sensation being the symptoms of over-ripening. As regards the bruising defects, they developed very slowly in cold storage, and even after 10 days were hardly visible. Fruits of both plum and prune cultivars were still characterized by an acceptable consumption quality, although slightly lower than of those picked manually. The fruits stored at 18 °C deteriorated quickly, and in that case, the negative effect of mechanical harvest on the appearance and consumption quality was statistically significant for 'Cacanska Lepotica' plum. A similar, but not significant tendency, was observed for 'Sweet Prune'. Extending fruit storage under room temperature conditions induced bruise transformation into red spots and intensified microbial spoilage, which was more pronounced for samples from the mechanical harvest. It can be concluded that the plum or prune crop collected with a harvester machine can definitely be stored in cold storage without substantial losses in its commercial value, especially when it is intended to be sold for processing purposes.

Consequences of mechanical harvesting for the trees

Mechanical fruit harvesting involves some damage to plum and prune trees. The straddle, canopy contact harvester that was working in this trial had no contact with the trunk or the tree leader. The shaking fingers were only touching young, one- to three-year-old shoots. The sealing/grabbing unit (which catches the fruits falling from the tree) was designed in such a way that the soft sealing scales had a wide deflection, up to 37 cm, and could smoothly open and close when passing the tree. After harvesting, one or two broken shoots could be found on several trees, but due to renewal pruning they were eliminated from the trees. Incidental bark damage was also observed on older branches. Again, the old branches were removed at pruning time, so such damage was unimportant. Summarizing, the temporary tree wounds did not affect the canopy shape, and after 3 years of mechanical harvesting, the trees were in the same condition as those harvested by hand picking.

Table 9. Comparison of changes in quality attributes of plum (‘Cacanska Lepotica’; big fruit, semi-dwarf rootstock) and prune (‘Sweet Prune’, small fruit, vigorous rootstock) harvested mechanically (M) and handpicked (H) during a storability test carried out in a cold-storage room and at ambient room temperature. Means for 2012-2014

Quality attribute*	Type of harvesting	‘Cacanska Lepotica’				‘Sweet Prune’			
		Cold storage 0 °C (days)		Room temperature 18 °C (days)		Cold storage 0 °C (days)		Room temperature 18 °C (days)	
		1	10	1	5	1	10	1	5
Appearance	M	3.3 a**	3.2 a	3.3 a	1.7 a	3.0 a	2.8 a	3.0 a	2.5 a
	H	3.5 a	4.0 a	3.8 a	3.0 b	3.3 a	3.3 a	3.3 a	3.0 a
Sign of fade	M	1.0 a	1.3 a	1.2 a	2.3 a	2.0 a	2.5 a	1.7 a	2.7 a
	H	1.0 a	1.2 a	1.0 a	1.8 a	1.5 a	1.8 a	1.8 a	2.5 a
Texture	M	2.8 a	3.2 a	2.8 a	1.6 a	2.5 a	2.5 a	2.5 a	2.0 a
	H	3.3 a	3.7 a	3.7 b	2.0 a	3.2 a	3.2 a	3.0 a	1.8 a
Sweet taste	M	3.2 a	2.7 a	3.2 a	3.3 a	4.3 a	4.2 a	4.7 a	4.2 a
	H	3.0 a	3.0 a	3.3 a	3.7 a	4.3 a	4.2 a	4.7 a	4.3 a
Acid taste	M	3.5 a	3.3 a	4.0 a	1.7 a	2.3 a	2.3 a	2.2 a	1.6 a
	H	3.8 a	3.5 a	4.3 a	1.8 a	2.6 a	2.3 a	2.5 a	1.6 a
Odd taste	M	1.0 a	1.3 a	1.0 a	1.5 a	1.3 a	1.8 a	1.5 a	2.2 a
	H	1.3 a	1.0 a	1.3 a	1.5 a	1.3 a	1.7 a	1.1 a	2.2 a
Flavor	M	3.5 a	2.8 a	3.2 a	2.8 a	4.2 a	2.8 a	3.8 a	2.3 a
	H	3.7 a	3.0 a	3.2 a	2.7 a	4.3 a	3.0 a	4.3 a	2.8 a
Consumption quality	M	3.7 a	3.2 a	3.3 a	1.8 a	3.2 a	2.6 a	3.2 a	2.1 a
	H	3.8 a	3.5 a	3.7 a	2.8 b	3.7 a	3.0 a	3.8 a	2.5 a

*Description of criterion values (1-5)

Appearance (1 – uninviting; 5 – very attractive), sign of fade (1 – none; 5 – clearly visible), texture (1 – very soft, 5 – firm), sweet taste (1 – delicate; 5 – very intensive), acid taste (1 – slight; 5 – very intensive), odd taste (1 – none/very slight; 5 – very intensive), flavor (1 – watery, empty taste; 5 – taste of fully ripe plum), consumption quality (1 – bad; 5 – very good).

**Different letters indicate significant difference between the types of harvesting under different storage conditions at p = 0.05 according to DMRT

DISCUSSION

Two factors, the cultivar and rootstock, play an important role in tree suitability for fruit harvesting with a straddle, canopy contact harvester working in continuous motion. All the fruits of the cultivars designed for mechanical harvesting should be ripe at the same time. Small-fruited cultivars (20-40 g) are more suitable than large-fruited cultivars (50-60 g). In this trial, the latter ones were more liable to bruising than the former. Fruits of the *Prunus* species (var. *Pruneliana*) are considered better at tolerating mechanical harvesting. Significant differences between cultivars in their susceptibility to bruising have also been found in mechanical harvesting of table olives (Morales-Sillero et al. 2014).

The recently observed worldwide trend towards high density planting (Peppelman et al. 2007) could also be applied in plum groves established for mechanical fruit harvesting in order to obtain earlier returns on investments, economical use of labor and production of high yields (Peppelman et al. 2007). In our trial, plums and prunes grafted onto a strong-growing rootstock and planted at high density were productive in fruiting and suitable for mechanical harvesting. However, the trees were difficult to manage and required a lot of tedious pruning. Semi-dwarf plum and prune trees seem to be the most suitable for the new technology of fruit harvesting. With moderate growth, such trees can be easily kept at the optimum size for the allotted space. Day et al. (2013) demonstrated that semi-dwarf plum trees planted at high density produce as much yield as large trees planted at low density.

Our way of planting and training trees for mechanical harvesting follows the suggestions of Ampatzidis et al. (2012) and Sarig (2012) to modify trees and orchard configuration to this new technology. Ferguson et al. (2010) advise a hedgerow system with limited width and height. The problem of plum and prune mechanical harvesting is closely related to the question of table olive harvesting. Morales-Sillero et al. (2014) suggest that olive trees should be kept in rows below 2.5 m to 3.0 m in height and 1.5 to 2.0 m in width. Similar canopy height and spread (2.8 m and 2.0 m) appeared to be optimum in our trial.

Straddle, canopy contact harvesters require trees with a regular leader and short, young, flexible branches. Plum and prune trees for planting obtained from a nursery always have a strong leader. This strong leader should be used for fast canopy training. It should be pruned lightly after planting the tree. To fill the leader with many lateral shoots, one might follow our method of tree training. New growing shoots on the top of the leader are pinched in May-June, and this treatment will stimulate numerous lateral shoots in the lower part of the leader.

Renewal pruning was introduced in England by Preston (1957) and diffused in Poland by Czynczyk et al. (1976). The idea of renewal pruning is simple. While pruning the tree leader, only one-, two- and three-year-old growth is left. Older wood is cut off. Such trees have an ideal structure for mechanical fruit harvesting because the fruiting wood is thin and flexible. The shaking rods of the harvester can easily move through the canopy. The fruits receiving impact from the shaking rods fall down avoiding excessive bruising. Our experiment showed that trees having only young wood, one to three years old, are able to bear enough fruit to be economically effective and suitable for mechanical harvesting.

Excessive vigor required hard pruning from the fifth year after planting to enable the harvester to move along the row. Moderately growing trees grafted on 'Wangenheim Prune' were kept to the required dimensions with light pruning. Large differences also appeared in growth intensity between the cultivars and planting distances. The new implemented methods of tree training induced the leader to fast vertical growth and the formation of numerous lateral shoots along it. All the trees reached the required height (2.8 m) in the fourth year after planting. In subsequent years, tree height had to be restricted by pruning to match the trees with the required parameters of the harvester, which had a 2.8 m clearance. For this reason, strong shoots appearing at the top of trees were removed from the 4th year on both machine and hand-harvested trees. Canopy spread increased until the sixth year from planting, but it was restricted by renewal pruning. Long old branches were replaced by shorter young shoots. This treatment assured uniform canopy spread.

Straddle, canopy contact, harvesters implemented to harvest fruit bushes work with an efficiency of 90-95%. When applied to harvesting tart cherry, the efficiency amounts to 90% (Mika et al. 2012). In harvesting olive trees, the efficiency is 80-90% (Castro-Garcia et al. 2012). There have been several suggestions (Morales-Sillero et al. 2014) towards improvement in the efficiency of the removal of fruits from the tree and collecting them. The most interesting is the experiment of Ampatzidis et al. (2012) with trellising cherry trees in a Y system and shaking fruits from thin aslant walls. In our trial, the efficiency of fruit removal and collection was 85-90%. Up to 10% of the fruits was lost by falling to the ground because of too strong growth of trees grafted on the 'Myrobalan' rootstock. During harvesting, vigorous summer shoots get caught by the harvester body and shake off the fruits in front of the collecting unit. In mechanical harvesting of table olives, difficulties were experienced (Morales-Sillero et al. 2014) in shaking off all the fruit. This was not a serious problem with plums because they are much heavier, so they receive a greater impact at shaking. The average harvest in kg fruit per 1 hour or per hectare is impressive. At high yields, the efficiency of mechanical harvesting was equal to that of 40 hand pickers. Such efficiency is imposing but not sensational when compared with table olive harvesting (Morales-Sillero et al. 2014), where mechanical harvesting efficiency was equal to nearly 300 person/hour hand picking fruits.

Bruising is considered the major limiting factor in mechanical fruit harvesting (Jiménez et al. 2011). Bruising occurs when fruits are touched by the shaking fingers, and when they fall onto thick limbs and into the harvester's catching system (Zipori et al. 2014). In our trial, all the listed factors were present, except for thick limbs, which were absent due to renewal pruning. However, each tree had a leader that could cause bruising. In our technology, all the fruits were suitable for processing, and only about 50% as table fruit after grading. Small-sized fruits were of better quality than large-sized fruits. Bruising was hardly visible soon after harvesting, so after grading the fruits were sold in a local market as table fruit. They were not of good quality for transporting because in cold storage, and especially at room temperature, they developed signs of bruising visible as red spots. In our opinion, to harvest table fruits mechanically, it is necessary to grow trees as a thin wall in a V or Y system, and harvest the fruit with a tractor-driven harvester.

CONCLUSIONS

1. Plum trees trained to the leader and pruned by the renewal method, adapted for mechanical harvesting, are able to develop a majority of fruit buds and abundant fruit set on young wood.
2. Plum trees spaced at 4 m between the rows and 1.5-2.0 m in the row, trained to the leader and subjected to renewal pruning, are suitable for hand and mechanical harvesting with a self-propelled straddle harvester working in continuous motion.
3. Trees grafted on a semi-dwarf rootstock appeared to be more suitable for mechanical harvesting than trees grafted on a vigorous rootstock.
4. The effectiveness of harvesting four cultivars with the combine harvester in three years was in the range 85-90%. At least 4 to 10% of plums were left on the tree or lost on the ground. Working efficiency of mechanical harvesting was 40 times higher than hand picking.
5. Up to 18% of the plums and not more than 10% of the prunes harvested mechanically showed some damage after harvesting. They can be fully acceptable for processing, for up to 10 days, providing the potential deterioration processes are inhibited by cold storage.
6. The large-fruited cultivars seem to be more susceptible to bruising than the small-fruited ones. For the latter, the share of marketable quality fruits within the mechanically harvested crop amounted to about 80%, which could be a good prognostic justifying further trials on the prune harvester.

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