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HARVESTING OF AGRICULTURAL WOOD RESIDUES FROM APPLE ORCHARDS USING A PRUNING ROUND BALER

In Europe, there are potentially large amounts of pruned biomass from orchards that could be used for energy production. One of the main barriers is a lack of complete technologies for mechanisation of the harvesting of these products. Under the EuroPruning project, a new baler adaptable to different site conditions was designed and constructed. The article presents the results of performance testing of the newly developed baling machine, conducted during the harvesting of pruning residues in apple orchards. The aim was to determine the potential yield of branches per unit area of orchard, harvesting losses, and the machine's efficiency, including its capacity and fuel consumption in two different operating configurations (with and without windrowers). It was shown that the average area rate was 1 ha/h, with a yield potential in the range 2.89-3.31 t·ha^{-1} *and fuel consumption of 4.5-5.1 dm*^{3}*·h*$^{-1}$*. Average harvesting losses measured in the studied orchards amounted to 22% with the machine working with activated windrowers and 37% without the use of windrowers.*

Keywords: pruning, wooden biomass, baling, harvesting losses, agricultural residues

Introduction

In Europe, bioenergy accounts for two-thirds of RES, and further growth in this figure is expected [AEBIOM 2015]. One of the reasons is the increase in interest in new biomass sources, such as residues from agricultural activities [Schubert et al. 2010], which are recognised as an additional and cost-effective local fuel.

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Large quantities of wood agricultural residues (ARs) can be obtained from the pruning of fruit orchards.

Ensuring high productivity and quality of fruit crops requires farmers to take numerous measures, including wood thinning by pruning, mainly carried out in winter and spring. For this reason, fruit orchards constitute a large, yet still untapped, source of woody biomass from annual pruning [Dyjakon et al. 2017]. Apple tree branches from sanitary pruning represent an important source of biomass which could be used for energy production. The global surface area occupied by apple orchards alone is ca. 5.0 million hectares [FAOSTAT 2014]. Assuming that one hectare of apple orchard provides on average 3.5 tonnes of pruned biomass during preservation pruning [Dyjakon et al. 2016], the potential yield of this valuable wood residue is over 17.5 million tonnes per year. Referring to the EU-27 countries, and taking account of other permanent crops (olives, vineyards, citruses, nuts and other fruits), the data collected during the EuroPruning project show that the total theoretical potential yield of pruning residues from these crops is 25.2 m tonnes per year [Garcia-Galindo et al. 2016b].

To date, pruning residues are seldom harvested and used for energy production. Depending on country, most of these ARs are mulched (shredded) or piled and burned at the field site. Sometimes, pruned biomass is raked using relatively simple tools attached to tractors, which makes the harvesting technology relatively inefficient [Garcia-Galindo et al. 2016a]. This is due to unsolved technical problems that occur during the harvesting operations, as well as to the lack of information concerning harvesting losses, the quantity and quality of residue biomass, as well as economic constraints. Additionally, orchards present difficult conditions for the operation of machines, due to the small inter-row spaces or diverse and uneven groundwork (soil, grass, stones, grooves or surface slopes), which affect in particular the productivity of harvesting [Acampora et al. 2013; Spinelli et al. 2014].

A good alternative is to collect the pruning residues during passes between the rows of trees. Currently, residue harvesting technologies can be divided into two processing techniques: pick-up and chipping (shredding) technologies, and pick-up and baling technologies. In the case of chipping, the machines are equipped with a storage system (bin) or blower (to direct the flow of the comminuted residues to an accompanying trailer). In the case of balers, the pruning residues are compacted into units of regular size and shape, tied and dropped on the ground for later collection.

It should be remarked that baling represents an additional step in the fuel production logistic chain, but it enables easier storage since bales can be stored even in the open air (this minimises or even eliminates any costs of wood drying). If the collected branches are to be burned not immediately after being harvested, but several months later, then the bales should simply be piled up, which enables natural drying. In the case of wood chips from orchards, open-air storage is not recommended, because fresh chips from fruit trees tend to decompose much faster [Germer et al. 2017]. Both systems might be enhanced by windrowers (installed in the front of the tractor or harvesting machinery), which move the cut branches to the middle of the row, increasing the collection capacity. Most pruning residue harvesting machine systems, depending on their size and optional equipment, are designed to work with farm tractors in the 50-70 kW class, and cost less than € 20,000. Many manufacturers have put solutions on the market, but there is not much data available about their practical performance and the efficiency of pruning residue harvesting.

In fact, research in this area has intensified in recent years, drawing more attention to harvesting efficiency and technology options focused on the pruning-to-energy (PtE) strategy, but this is mainly related to chipping systems (pick-up, chipping and storage in a bin/chamber/trailer) [Velazquez-Marti et al. 2009; Spinelli and Picchi 2010; Acampora et al. 2013; Boschiero et al. 2015; Nati et al. 2017]. The chipping system seems to be more popular in permanent crop plantations (e.g. vineyards), but its main disadvantages are high energy inputs during harvesting (pruning pickup and comminution) and stricter requirements related to the preparation of wood chips for storage (the use of a drying process). For example, tests performed in a peach orchard showed that the fuel consumption of the machinery (tractor and chipper equipped with windrowers) was ca. 11.93 $dm^3 \cdot h^{-1}$ with an effective field capacity of 0.31 $ha \cdot h^{-1}$ and a pruned biomass yield of 2.44 $t \cdot ha^{-1}$ (moisture content 41.2%) [Pari et al. 2018]. As regards harvesting technology based on baling of the pruned biomass in orchards, available information is very limited [Spinelli et al. 2010], especially in relation to harvesting losses and the capacity of the technology. There have been only a few studies concerned with harvesting losses with the use of a mini-baler or big baler [Magagnotti et al. 2013; Spinelli et al. 2014]. Unfortunately, little is known about the harvesting losses and energy inputs in case of the use of a big baler equipped with windrowers moving the cut branches into the middle of the passing track.

The goal of the present study was to determine the productivity, harvesting losses and fuel consumption of a new system consisting of newly developed baling machinery equipped with a pick-up set, baling chamber and windrowers (to improve the collection of the cut branches), and to compare the results with those obtained for the same system working without windrowers. If the new system proved functional and effective, it would represent a feasible option to increase the amount of wooden biomass collected for use in energy production, without requiring any significant change in crop establishment and management techniques.

Materials and methods

The tests were carried out in two apple orchards located in the district of Potsdam-Mittelmark (Brandenburg, Germany). The first orchard (Orchard 1) was situated near the town of Werder (Havel), and the other (Orchard 2) in the municipality of Groß Kreutz. In both cases, the width of the inter-row spaces was 3.5 m, and the tree spacing in a row was 1.2 m (table 1). The age of the trees was 8 years in Orchard 1 and 13 years in Orchard 2. The tested object was the innovative pruning round baler (PRB), model PRB 1.75 (fig. 1) [Frąckowiak et al. 2014], designed as part of the EuroPruning project. Thanks to the four wheels located in the underbody of the baler, this is the first machine on the market whose width is less than 2.0 m and which is able to harvest pruned biomass from orchards and plantations and to produce cylindrical bales of typical size for standard straw and hay bales (1.2 m in height, 1.2 m in diameter). Moreover, the

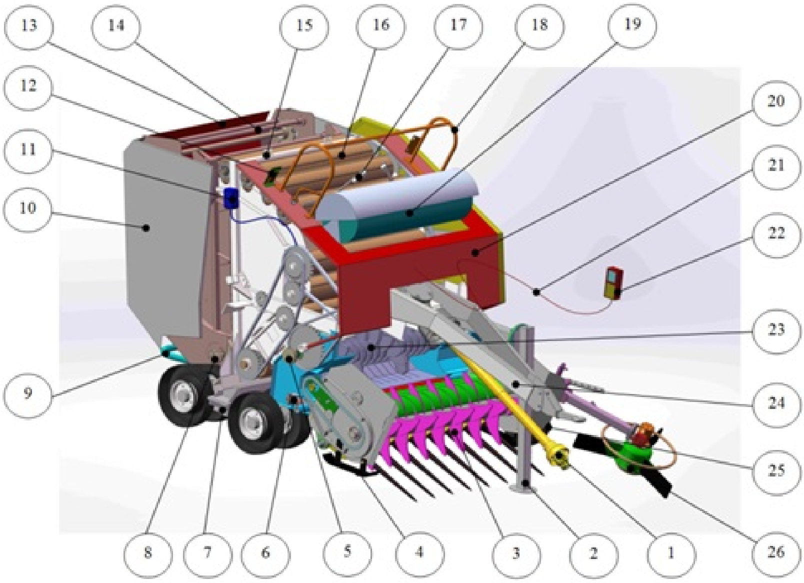

Fig. 1. Pruning round baler (model PRB 1.75): 1 – Wide-angle PTO shaft, 2 – Jack stand, 3 – Finger-type loader, 4 – Pick-up skid, 5 – Safety clutch, 6 – Pick-up hydraulic cylinder, 7 – Wheel axle, 8 – Rolling chamber lock, 9 – Bale ramp, 10 – Tailgate, 11 – Oil tank of central lubrication system, 12 – Indicator of degree of filling of the rolling chamber, 13 – Back cover, 14 – Bar conveyor, 15 – Lift eyes, 16 – Compression rollers, 17 – Twine binding device with hydraulic hoses, 18 – Binding device cover, 19 – Net wrapping system, 20 – Storage box for twine, 21 – PILOT BOX connecting cable, 22 – Control panel (PILOT BOX), 23 – Transport rotor, 24 – Drawbar with ring hitch and height adjustment, 25 – Pick-up gauge wheel, 26 – Windrower

pruned biomass pick-up assembly has a controlled height-adjustment system. Height is controlled by copying wheels (in flat grassy fields) or anti-sinking skids (in stony ground conditions). Additionally, the baler is fitted with adjustable working angle and height tines, avoiding the collection of stones from the ground and improving the quality of the baled material. Finally, the machine is equipped with windrowers driven hydraulically from the tractor system, whose role is to improve the process of branch harvesting by reducing losses and, above all, by eliminating the additional stage preceding the harvest, namely manual or mechanical sweeping of branches to the centre of the inter-row spaces. The operating range of the windrowers can be regulated [Adamczyk et al. 2014; Frąckowiak et al. 2016].

During all tests, the baler machine was used with the same tractor: a Massey Ferguson 4270, with a power of 84 kW. The machine was operated by the same tractor driver in both orchards. The unit (machine and tractor) moved independently without the aid of a truck from Orchard 1 in Werder (Havel) to Orchard 2 in Groß Kreutz. Both orchards were located on flat terrain. Characteristics of the tested orchards and the PRB prototype are given in tables 1 and 2.

Table 1. Characteristics of the tested orchards

Feature, parameter	Unit	Orchard 1	Orchard 2
Area tested	ha	1	10
Tree spacing	m	3.5 × 1.2	3.5 × 1.2
Headland width	m	7.5 and 10	10 and 10
Plantation depression angle	°	0	0
Distribution of rows with branches	ratio	1:1*	1:1*
Thickness of windrow	m	0-0.1	0-0.3

*1:1 – branches for harvesting located in each inter-row space

Table 2. Characteristics of the tested machinery (model PRB 1.75)

Feature, parameter	Unit	Data/Value
Tractor type	–	MF4270
Tractor power	kW	84
Bale shape	–	cylinder
Average bale diameter	m	1.2
Average bale height	m	1.2
Operating width of machine:		
– without windrowers	m	1.75
– with windrowers	m	3.4

Data collection involved detailed testing carried out within one working cycle, where the production of one bale was treated as one complete cycle. The cycle time was properly defined and divided into elements and sections for activities treated as typical for the functional process of the tested machine [Björheden 2008]. Normally, detailed analyses of the duration of individual activities are more discriminative than tests for the entire cycle (shift-level) and allow the detection of smaller differences between groups [Olsen et al. 1998].

The yield of branches was determined by weighing the bales, and losses were estimated by collecting and weighing left-overs from the surface where the bale had been collected. Bales and losses were weighed using certified dynamometric balances. As in previous studies [Spinelli et al. 2010] the bales were weighed on a suspended balance, and the losses using a hand balance.

Moisture content was determined in the laboratory. Moisture content tests were conducted on three individual samples, randomly collected from each orchard at the time of branch cutting and during harvesting by the PRB. Random samples were placed in tightly closed bags and moved to the laboratory, and then weighed, fresh and after drying for 24 hours at 105°C, in a ventilated furnace in accordance with European Standard EN 14774-1:2010.

The inter-row spacing, spacing of trees in rows, width of headlands and length of rows were measured using a laser distance meter. The length of random branches was measured with measuring tapes, and their diameters at the thickest point per branch were measured with slide callipers. For branches whose measured diameters exceeded the assumed maximum allowable value for safe operation of the PRB, the section where the excess existed was measured.

An important aspect of assessment of the operation of the PRB is the analysis of the quantity of losses, i.e. branches remaining in an inter-row space after the machine has passed. Each measurement area had a width equal to the width of the inter-row space and a length five times the width of the inter-row space.

Prior to each cycle, the fuel tank in the tractor was completely filled. After the cycle, the fuel was refilled with fuel stored in a canister. The mass of the fuel consumed by the tractor to perform one complete working cycle was estimated by determining, using a hand scale, the mass of the fuel canister before and after refilling of the tractor's tank. The determined mass of fuel was converted to a volume, assuming the density of diesel oil to be 830 $kg \cdot m^{-3}$ [EN 590:2013].

To characterise the performance of the PRB, the average productivity of the machine, pruned biomass yield (of branches) and quantity of losses were calculated, as well as the variability of these parameters [Spinelli et al. 2010]. The obtained values were used to create a simple spreadsheet tool which enables determination of the correlations of these data as functions of independent variables entered by the user. More realistic, precise and discrete models of the process are not expected to offer a considerable increase in forecasting precision when used for such simple process chains [Björheden 2008].

Results and discussion

Branches were collected from an area of 1 ha both in Orchard 1 (fig. 2) and in Orchard 2 (fig. 3). In each orchard, 12 bales were collected from that area during the tests. As a result, the test duration included 24 cycles, involving the production of 24 bales. The average yield of pruned branches was similar in both cases: 3.31 $t{\cdot}ha^{-1}$ for Orchard 1 and 2.89 $t{\cdot}ha^{-1}$ for Orchard 2 (table 3).

a) pruned biomass in Orchard 1

b) PRB 1.75 in operation

Fig. 2. Pruning round baler testing in Orchard 1

a) pruned biomass in Orchard 1

b) PRB 1.75 in operation

c) pile of pruned biomass bales

Fig. 3. Bales of apple pruning wood collected from Orchard 2

In Orchard 1, the length of one inter-row space was 100 m. In Orchard 2 it was much greater, at 300 m. In both orchards, the collected branches were distributed over the entire inter-row width. However, the thickness of the windrow (the height of the cut pruned biomass layer) was different: 0.1 m in Orchard 1 and 0.3 m in Orchard 2.

Table 3. Characteristics of the collected pruned biomass

Feature, parameter	Unit	Orchard 1	Orchard 2
Average branch diameter	mm	19 +/-10	25 +/-13
Average branch length	mm	1105 +/-325	985 +/-260
Average branch yield	$t{\cdot}ha^{-1}$	3.31 +/-0.11	2.89 +/-0.09
Moisture content of branches	%	46.30	44.25

The width of headlands had a significant influence on the route of test passes. For Orchard 1, the headland width was only 7.5 m at one end and 10.0 m at the other. The headlands of Orchard 2 had the same width of 10.0 m at both ends.

The machine is designed for harvesting and baling branches with diameters of up to 35 mm. Thicker branches (up to 50 mm in diameter) may be collected if the section on which the normal maximum diameter (35 mm) is exceeded is not longer than 300 mm.

The average productivity obtained during testing was 3.10 $t{\cdot}h^{-1}$ for operation without windrowers, and 3.21 $t{\cdot}h^{-1}$ for operation with windrowers (table 4).

The use of windrowers also affected the fuel consumption and the area harvested per bale. With the use of windrowers, the fuel consumption per tonne increased and the area harvested to produce one bale decreased (tables 4 and 5). The average fuel consumption measured in the orchard was approx. 4.9-5.1 $dm^3{\cdot}t^{-1}$ of collected biomass during operation with windrowers and 4.5-4.6 $dm^3{\cdot}t^{-1}$ without windrowers.

Table 4. Operating characteristics of the PRB

Feature, parameter	Unit	Orchard 1	Orchard 2
Productivity:			
– without windrowers	$t{\cdot}h^{-1}$	3.05 +/-0.15	3.15 +/-0.20
– with windrowers	$t{\cdot}h^{-1}$	3.15 +/-0.20	3.27 +/-0.20
Fuel consumption during operation:			
– without windrowers	$dm^3{\cdot}h^{-1}$	4.5 +/-0.10	4.6 +/-0.10
– with windrowers	$dm^3{\cdot}h^{-1}$	4.9 +/-0.10	5.1 +/-0.10
Average losses:			
– without windrowers	%	37.3 +/-3.1	41.3 +/-4.2
– with windrowers	%	22.1 +/-2.5	20.9 +/-2.4

Table 5. Characteristics of bales formed by the PRB (N=5)

Feature, parameter	Unit	Orchard 1	Orchard 2
Quantity of bales	pcs	12	12
Average (+/-S.D.) bale weight	kg	240.5 +/-32.1	261.8 +/-19.5
Average bulk density of one bale	kg·m^{-3}	213	215
Average area of orchard per bale:			
– without windrowers	m^2	1050	1024
– with windrowers	m^2	875	915

The obtained values indicate that with windrowers, at the expense of increased fuel consumption, a larger amount of biomass is collected. In the cases considered, around one hundred kilos of additional pruned fresh biomass (moisture content 55%) harvested by the baler with operating windrowers was associated with an increase in fuel consumption by ca. 0.5 dm^3. Assuming that the lower calorific values of diesel fuel and dry apple tree branches are 51.5 MJ·kg^{-1} (fuel density 0.830 kg·dm^{-3}) and 18.0 MJ·kg^{-1} respectively [Spinelli and Magagnotti 2011; Dyjakon 2018], a positive result is achieved for the energy balance (EB) defined as the difference between the energy input and energy output during the process [Borjesson 1996]. The calculations showed that a supplementary fuel energy input of 21.4 MJ·h^{-1} leads to an additional 990 MJ·h^{-1} of chemical energy output accumulated in the harvested biomass, resulting in an EB index of 968.6 MJ·h^{-1}. This indicates that the use of windrowers has a positive impact on the harvesting process when viewed in terms of the PtE strategy.

Another analysed parameter of the process of baling of biomass (branches) was the number of uncollected branches left by the PRB, referred to as harvesting losses. Losses normally include all branches left in the inter-row space which should have been collected by the machine according to their dimensions (diameter and length). Losses do not include branches whose dimensions exceeded the values assumed as the maximum allowable for harvesting by the PRB. The analysis also concerned the data relating to the inter-row spaces where windrowers operated and where they were not used. In the case of operation of the PRB with windrowers the pruning losses in Orchards 1 and 2 were 22.1% and 20.9% respectively, while without active windrowers the losses increased to 37.3% for Orchard 1 and 41.3% for Orchard 2. The increase in pruning losses arises from the fact that active windrowers raked additional amounts of cut branches into the range of the pickup system of the PRB 1.75 machine. Without operating windrowers the PRB machine passes by the area where some branches have been thrown during the previous operation (tree pruning). This proves also that additional devices (windrowers) installed (built-in) in the PRB machine increase its functionality and the quantity of pruned biomass harvested during passes between the tree rows (fig. 4). It should be noted that neither orchard had been prepared for professional harvesting of the pruned biomass; that is, the workers performing sanitary pruning of the apple trees cut the branches without paying attention to where they would fall. As a result, the harvesting machine could not reach all of the places where branches lay (even with active windrowers). This might partly explain the higher pruning losses measured during these tests in comparison with results obtained by other researchers [Grella et al. 2013; Magagnotti et al. 2013]. On the other hand, it seems that in case of biomass harvesting for energy production, the pruning operation (branch cutting) should also be properly adjusted to facilitate later collection of the branches and improve the harvesting efficiency.

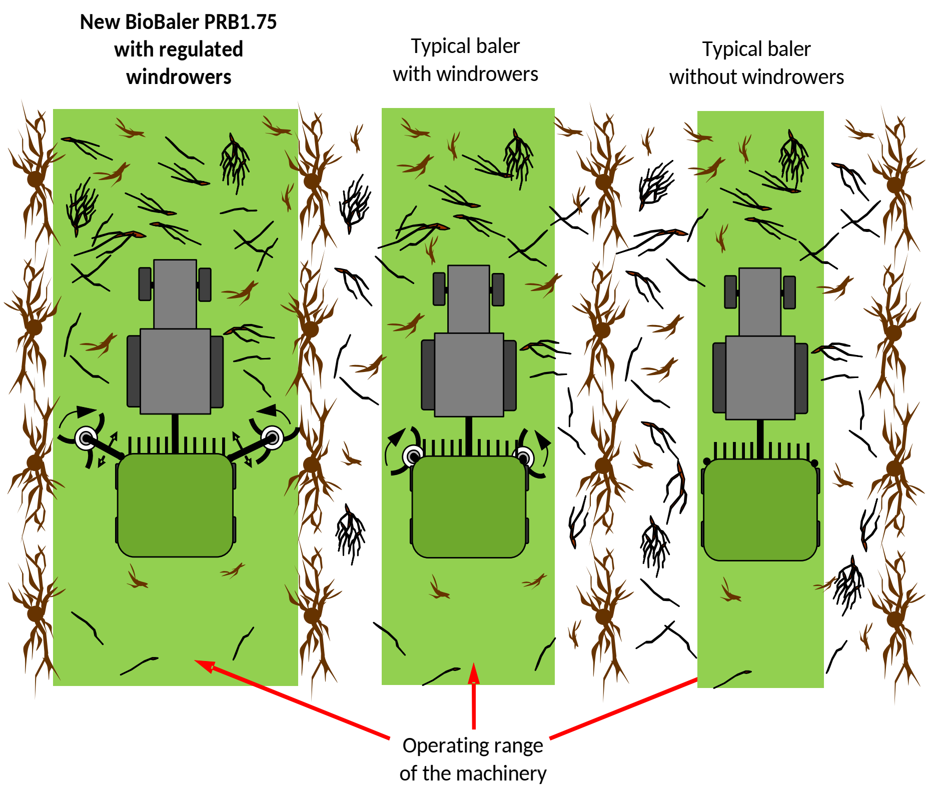

Fig. 4. Operating range of balers

Parameter estimates are presented in table 6. For both analysed variables (machine operation with and without windrowers) the number of replications was N = 5 [ISO 2602:1980]. No outliers were identified using the Q-Dixon test [Greń 1974]. Additionally, analysis of normality was performed using the Shapiro-Wilk test. Data on pruning losses left in the inter-row spaces after passes of the PRB machine were normally distributed for performance test samples with and without windrowers (Shapiro-Wilk test, $p > 0.05$).

Table 6. Results of statistical analysis of losses during operation of the PRB

Feature, parameter	Unit	Orchard 1	Orchard 2
Mean $\bar{x}$:			
– without windrowers	$kg \cdot m^{-2}$	0.12	0.11
– with windrowers	$kg \cdot m^{-2}$	0.07	0.06
Standard deviation *SD*:			
– without windrowers	$kg \cdot m^{-2}$	0.01	0.02
– with windrowers	$kg \cdot m^{-2}$	0.02	0.02
Confidence interval *E:*			
– without windrowers	$kg \cdot m^{-2}$	0.09; 0.14	0.07; 0.15
– with windrowers	$kg \cdot m^{-2}$	0.05; 0.07	0.05; 0.07
Spread measure:			
– without windrowers	–	0.04	0.06
– with windrowers	–	0.03	0.04
Critical parameter of Q-Dixon test:			
– without windrowers			
max	–	0.25	0.17
min	–	0.50	0.50
– with windrowers			
max		0.33	0.25
min		0.33	0.25
Significance (Student's *t*-test)	–	2.0612	1.1845

The PRB operating without windrowers resulted in significantly higher losses compared with operation with windrowers, in both orchards (Student t-test, Orchard 1 $t = 2.0612$, Orchard 2 $t = 1.1845$, $p < 0.05$). Therefore, to increase the productivity of pruned biomass harvesting, the use of windrowers is recommended. However, it should be remarked that the use of windrowers entails increased fuel consumption. As a consequence, from an economic standpoint, the increase in the productivity of the baler machine needs to be analysed with reference to fuel costs and profits from the sale of the biomass.

Recommendations and comments

The tests carried out lead to a general assessment of the analysed technological process and of the processing machine. However, as has also been noted by other researchers [Spinelli et al. 2010], there are many factors influencing the harvesting process and its productivity, and therefore the results should be applied with caution.

The tested PRB is specially designed to harvest branches lying in inter-row spaces after sanitary thinning in orchards, fruit bush plantations and vineyards. The special design resulted from the need to minimise the width of the machine to enable proper operation in plantations with limited space [Recchia et al. 2009].

It is commonly known that the harvesting of a material such as branches remaining after pruning carried out in orchards, fruit bush plantations or vineyards is a seasonal activity [Romański et al. 2014]. On the other hand, the low cost of storage and natural drying of the collected material in the form of bales permits the less intensive use of the PRB than in the case of other machines (such as chipping machines). Nevertheless, the harvesting and processing of the residues after pruning entail certain costs. The total costs are affected by the limited efficiency of the machinery and equipment used in the system. The task of increasing the hourly output of the PRB may be a challenging one. It is dependent on the quantities of cut branches lying in the inter-row space [Spinelli and Picchi 2010; Spinelli et al. 2014]. The losses during harvesting are also affected by the pruning procedure. If the farmer plans to harvest the prunings, the cut branches should be thrown in proper locations to facilitate their collection by the machine. A proper approach and good practices on the part of the workers, as well as their orchard experience, may minimise the losses and increase the yield of pruned biomass. It should also be remarked that the biomass yield from the orchard depends greatly on the age and type of the trees. With a small yield of branches per hectare, harvesting by baling may become unprofitable due to the low productivity and high operating costs resulting from the quantity of fuel consumed per unit weight of collected branches, depreciation of the machine, and the workload of the operator. The productivity and costs of harvesting are also affected by the operating speed of the tractor–baler unit. In the case of straw baling, the average speed is approximately 10 $km \cdot h^{-1}$, while during operation in the orchard, due to the operating conditions (passage between tree crowns, the need for the operator to pay attention to branches protruding from crowns in addition to controlling the work of the baler assemblies), the average operating speed was approximately 5-6 $km \cdot h^{-1}$. Increasing this speed may adversely affect the level of losses and the comfort of the operator's work.

Conclusions

With a view to improving the productivity indices for branch harvesting in fruit orchards and mechanising the activities involved, the developed PRB 1.75 baler was tested with and without the use of windrowers.

The average area rate achieved by the PRB was 1.0 ha·h^{-1}, and the average value of losses was measured at approximately 20% with activated windrowers and 40% without the use of windrowers. Average effective hourly productivity was in the range 3.0-3.3 t·h^{-1}. Moreover, operation of the windrowers led to a net positive energy balance of almost 970 MJ·h^{-1}, which reflects an increase in the final value of the chemical energy accumulated in the pruned bales and in the energetic potential of this technology. The tests of the PRB demonstrated that it may be a cost-effective and productive means of harvesting material intended for energy production.

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