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Performance Assessment of Front-Mounted Beet Topper Machine for Biomass Harvesting

Volodymyr Bulgakov [1], Simone Pascuzzi [2,*], Semjons Ivanovs [3], Francesco Santoro [2], Alexandros Sotirios Anifantis [2] and Ievhen Ihnatiev [4]

1 Department of Mechanics, Faculty of Construction and Design, National University of Life and Environmental Sciences of Ukraine, 03041 Kyiv, Ukraine; vbulgakov@meta.ua

2 Department of Agricultural and Environmental Science, University of Bari Aldo Moro, Via Amendola 165/A, 70126 Bari, Italy; francesco.santoro@uniba.it (F.S.); alexandrossotirios.anifantis@uniba.it (A.S.A.)

3 Faculty of Engineering, Latvia University of Life Sciences and Technologies, LV-2130 Jelgava, Latvia; semjons@apollo.lv

4 Department of Machine-Using in Agriculture, Dmytro Motornyi Tavria State Agrotechnological University, 18, Khmelnytskiy Ave., 72312 Melitopol, Ukraine; yevhen.ihnatiev@tsatu.edu.ua

* Correspondence: simone.pascuzzi@uniba.it; Tel.: +39-080-544-2214

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Abstract: Sugar beet is an extensive crop of great agronomic value with significant productive and economic returns and Ukraine's sugar beet accounts for about 5.1% of the overall world production. Sugar beets and the by-products resulting from its manufacturing transformation are a significant renewable energy resource. A new high-quality performance prototype of a sugar beet top harvester, front mounted on a tractor, was built by the authors in Ukraine. The aim of this study is to evaluate the main performance parameters related to the operation of this new machine. Field tests were carried out linking the prototype to a wheel tractor, whilst suitable sensors measured the significant kinematic and dynamic parameters, allowing experimental data collection to assess the machine's performance parameters. The entire technological process of harvesting and transporting the beet tops to the beet top storage unit required power ranging from 6.42 to 17.65 kW. At the topmost tested forward speed, the required tractor traction force was less than 1.9 kN with the power required by the shaft that drives the screw conveyor ranging from 3.1 to 4.6 kW. This value was the lowest for a speed of the tractor–beet top harvesting machine aggregate ranging from 0.9 to 1.2 m·s^{-1}.

Keywords: sugar beet; beet top cutting; tractor–harvester aggregate; biomass

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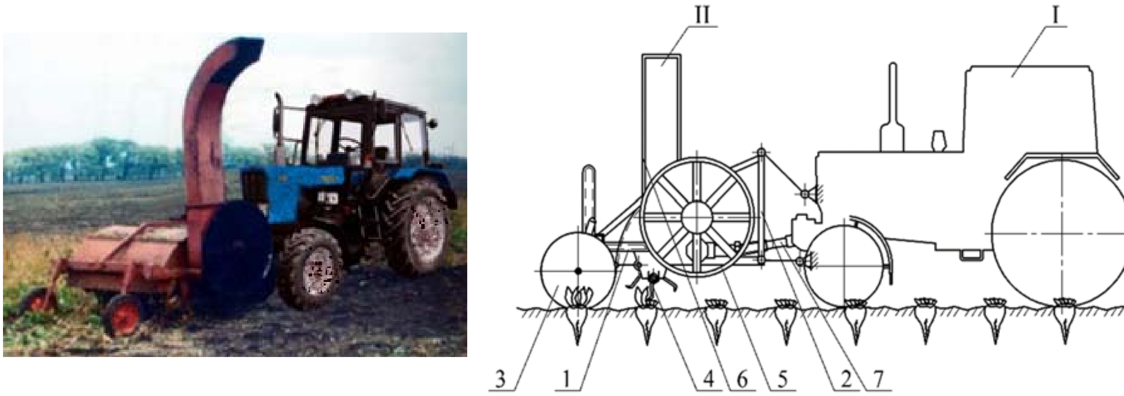
1. Introduction

World sugar beet production amounts to approximately 2.75·10^8 ton with a devoted area of 2.7·10^8 m^2 [1]. In terms of both production and harvested area, referring to overall world data, the EU contribution is 43.5% and 36.3%, respectively, with the most contributive countries being France and Germany with 14.4% and 10.1%, respectively, and 9.5% and 8.6%, respectively, while Italy contributes only 0.7% for both ratios. Referring instead to Ukraine, the previously referred ratios are 5.1% and 5.7%, respectively [1]. However, it should be mentioned that beet and sugar production regulation within the EU is based on the Common Market Organization (CMO) and that, in 2006, the CMO was completely amended, leading to a strong reduction in EU sugar production [2]. Some countries such as France and Germany, considered more suited to beet production and more efficient from an industrial point of view, have been little affected by the changes, whereas others such as Italy have suffered significant consequences. Italy, at the time active in the sector with 19 sugar industries and approximately 1.4·10^9 m^2 of beet-cultivated area, after the reform gradually reduced their industrial plants from 19 to 4 and their overall beet-cultivated area decreased considerably [2]. Sugar beet is an extensive crop of great agronomic value with significant productive and economic returns; moreover, it has always been considered an "improvement crop" from which all crops in succession benefit [3–6]. Sugar beet and the by-products resulting from its industrial transformation are a noteworthy renewable energy resource [7–10], e.g., pulps can be used in biogas and electricity production [11–15], and beet leaves and tops are currently used as a fundamental component in the food rations of animal farms, as they are rich in nutrients and they can be employed as a substrate in anaerobic digestion for renewable energy production, due to the high content of both sugar and almost completely digestible fibers [16,17]. Furthermore, large amounts of the sugar industry's different kinds of generated waste, such as sugar beet pulp and leaves, can be employed as precious substrates in the production of biotechnology cellular proteins, enzymes, organic acids, etc. [18–20]. For all the aforesaid reasons, a high performance and quality of sugar beet top harvesting that can be achieved only using specialized machines clearly appears to be of paramount importance [21–24]. The beet harvesting machines commonly used in Europe do not meet these performance standards, in particular referring to the beet tops which are not collected after cutting but simply crushed and spread on the soil in such a way that makes them unusable also for animal fodder [25–27]. Furthermore, even in the case of high-performance beet harvesting machines, some specific conditions, such as those in Ukraine, may arise from which many unresolved problems still could derive. For example, one of these problems is a deterioration in the quality of the collected beets, especially in difficult harvesting conditions, such as high soil hardness or excessive humidity, the irregularity and non-linearity of the crop rows, excessive weeds, and so on [28–33]. Therefore, the scientific and research community continue to search for design and technical solutions in order to meet these operative needs and, at the same time, reduce the energy required by the digging and harvesting process of the beets, so increasing the productivity and reliability of the machines [34–39]. The study, design and prototyping of a new sugar beet top harvester in Ukraine that, when front mounted on the tractor, considerably increases beet top harvesting performances has to be considered in this framework [40–42]. According to experimental data obtained from field tests, the aim of this study was to evaluate the main performance parameters related to the operation of this new machine.

2. Materials and Methods

2.1. The Beet Topper Machine

The research focuses on a new three-row beet top harvesting machine equipped with improved working devices which allow the machine to cut the beet tops and transport them into a loading chute [43–46]. In particular, the developed front-mounted beet top harvester is founded on the concept of a mower-shredder and is mounted on a wheeled tractor (Figure 1a), from which it receives motion and power by means of a cardan universal joint (7 in Figure 1b) linked to the power take-off of the tractor itself. The beet top harvester continuously cuts rosette leaves during its forward motion, regulating the cutting height of a cylindrical rotor (4 in Figure 1b) equipped with arc-shaped knives by means of pneumatic feeler wheels (3 in Figure 1b), ensuring an effective result in the cutting of beet tops [47]. Once cut, the beet tops are transferred onto a screw conveyor that ensures their transportation into a loading chute (6 in Figure 1b) and subsequent delivery into a trailer running alongside through a chute. The main technical characteristics of this new beet top harvester are: (i) three sugar beet root crops rows working at a width of 1.35 m, (ii) a forward speed of up to 2.1 m·s^{-1}, (iii) a mass equal to 850 kg, (iv) a working capacity within a range of 1.0–1.2 ha·h^{-1} [41].



(**a**) (**b**)

Figure 1. Tractor–harvester aggregate: (**a**) photo taken during experimental field test phase, (**b**) schematic representation: I—Wheeled, row-crop integrated tractor; II—Front-mounted beet topper machine: 1—frame, 2—point hitch, 3—pneumatic feeler wheel, 4—rotary beet top cutting device, 5—screw conveyor, 6—loading chute, 7—cardan universal joint.

2.2. The Field Tests

The experimental tests took place in the Vasilkovsky district, Kiev Region, and were aimed at assessing the main performance parameters of the new three-row beet top harvester in the typical operating conditions of the harvesting phase. The beet topper machine was joined at the front of a wheeled MTZ-80 tractor using a semi-mounted coupling through the three-point hitch, deriving the needed motion from the tractor power take-off (PTO) (Figure 1). Throughout the whole duration of the experimental tests, the tractor rear axle was the only drive axle with the front one disabled. The following performance parameters during the carried-out tests were taken into account [48,49]: (i) the tractor traction power N, kW; (ii) the tractor traction force R, N; (iii) the required torque at the tractor PTO T_{PTO}, N·m; and (iv) the required power at the tractor PTO N_{PTO}, kW, which is related to T_{PTO} and to the PTO shaft angular speed ω_{PTO} through the equation $N_{PTO} = T_{PTO} \cdot \omega_{PTO}$. The tractor traction power (N) was measured using sensors able to measure torque and the angular speeds of the tractor rear left and right drive axle shafts, whereas the tractor traction force (R) was given by [50,51]:

$$R = \frac{N}{V} \tag{1}$$

where V, m·s^{-1} is the aggregate tractor–beet top harvester forward speed.

The tractor's left and right rear drive axle shaft's torques and angular speeds were measured by means of Zemic BA350KA (Zemic Europe B.V.—Etten-Leur, The Netherlands) contactless rotary torque transducers, capable of gauging both the torque strain in the shafts, via an on-shaft microprocessor circuit, and shaft rotational speed, and whose main features are: 1000 Ω nominal resistance and a −30 to +80 °C working temperature range.

The actual tractor–beet top harvester aggregate forward speed was measured through a track measuring wheel equipped with an Autonics PR12-4DN stationary proximity sensor (Autonics, Busan, South Korea) whose main characteristics are: cylindrical round (PR Series) type, 12–24 V DC voltage, M12 sensing side diameter, 4 mm sensing distance, 500 Hz response frequency (Figure 2).

Figure 2. Tractor–harvester aggregate actual speed measuring wheel.

The torque T_{PTO} and power N_{PTO} required by the PTO were evaluated through the same aforesaid Zemic BA350KA (Zemic Europe B.V.—Etten-Leur, The Netherlands) sensor arranged on the tractor PTO (Figure 3).

Figure 3. Required torque and power sensor arranged at the tractor power take-off (PTO).

All used sensors were connected to a laptop via an L-CARD model E14-140-M (Moscow, Russian Federation) converter whose main characteristics are: a 48 MHz 32 bit processor, 8 differential (16 if common ground is used) input channels.

The tests were carried out maintaining both the engine crankshaft and tractor PTO speeds at 1200 rpm and 540 rpm, respectively, and considering three different forward speeds of the tractor–harvester aggregate, obtained by means of three different gear-range lever combinations: (i) 1st gear and the high speed ratio range lever engaged with an estimated forward speed of V = 1.46 m·s^{-1} (5.27 km·h^{-1}); (ii) 2nd gear and the low speed ratio range lever engaged with an estimated forward speed of V = 1.88 m·s^{-1} (6.78 km·h^{-1}); and (iii) 3rd gear and the high speed ratio range lever engaged with an estimated forward speed of V = 2.49 m·s^{-1} (8.97 km·h^{-1}). In these conditions, tests were carried out within the manufacturers' recommended forward tractor–harvester aggregate speed range of 0.9–2.50 m·s^{-1} (3.2–9.0 km·h^{-1}) and for each gear-range lever combination, three repetitions were carried out while measuring actual tractor–harvester aggregate speed.

Furthermore, for each chosen gear-range lever combination, three different screw conveyor angular speeds were considered (5 in Figure 1b). In particular, whilst maintaining a constant at 57 rad·s^{-1} (540 rpm), the angular speed of both the tractor PTO and the shaft that drives the cylindrical rotor equipped with beet top cutting knives, three different angular speeds of screw conveyor driving were considered: (i) $\omega_{po1} = 57$ rad·s^{-1}; (ii) $\omega_{po2} = 39$ rad·s^{-1}; and (iii) $\omega_{po3} = 0$ rad·s^{-1} (Figure 4).

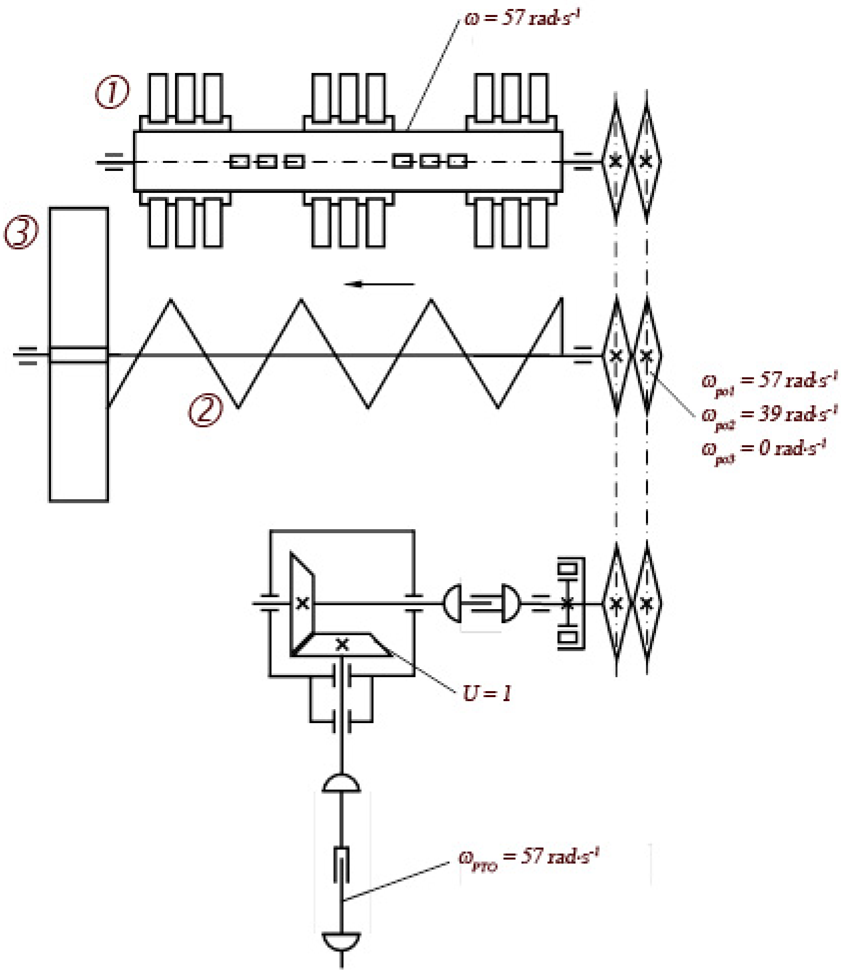


Figure 4. Kinematic diagram of the tested three row beet top harvester: 1—rotary beet top cutting device, 2—screw conveyor, 3—loading chute feeder.

2.3. Data Analysis

The experimental data were processed using Microsoft Excel software in order to carry out a regression analysis of each studied performance parameter, by means of the least-squares method [52]. As is known, this criterion is a technique for fitting the "best" curve to the sample $\hat{x}$, $\hat{y}$ observations. It involves minimizing the sum of the squared (vertical) deviations of points from the curve:

$$Min \sum (\hat{y}_i - y_i)^2 \quad (2)$$

where:

$\hat{y}_i$ refers to the actual observations
y_i refers to the corresponding fitted values, so that $(\hat{y}_i - y_i) = e_i$, the residual [52].

The data were processed using different regression functions (linear, polynomial, power and exponential), calculating the corresponding coefficients of the determination R^2 and residuals. Among these regression functions, only the 2nd order polynomial was considered, because for all the examined performance parameters, it allowed the achievement of the highest value of R^2 and the lowest residuals. The 2nd order polynomial was given by:

$$p(x) = a_0 + a_1 x + a_2 x^2 \quad (3)$$

where the coefficients a_0, a_1 and a_2 were calculated by the solution of the following matrix system:

$$\hat{V}^t\hat{V}A = \hat{V}^t\hat{Y} \tag{4}$$

where:

$\hat{V}$ is a Vandermonde matrix, which contains the observation values $\hat{V}_{i,j} = \hat{x}_{i-1}^{j-1}$;
$\hat{V}^t$ is the transpose matrix of $\hat{V}$;
A is the column vector of the terms a_i;
$\hat{Y}$ is the column vector of the observations $\hat{y}_i$.

Practically, considering the 9 couples of experimental measures for each studied performance parameter, the linear matrix system (4) gives:

$$\hat{V}^t\hat{V} = \begin{pmatrix} 1 & 1 & 1 & \dots & 1 \\ \hat{x}_0 & \hat{x}_1 & \hat{x}_2 & \dots & \hat{x}_8 \\ \hat{x}_0^2 & \hat{x}_1^2 & \hat{x}_2^2 & \dots & \hat{x}_8^2 \end{pmatrix} \begin{pmatrix} 1 & \hat{x}_0 & \hat{x}_0^2 \\ 1 & \hat{x}_1 & \hat{x}_1^2 \\ 1 & \hat{x}_2 & \hat{x}_2^2 \\ \dots & \dots & \dots \\ 1 & \hat{x}_8 & \hat{x}_8^2 \end{pmatrix} = \begin{pmatrix} z_{1,1} & z_{1,2} & z_{1,3} \\ z_{2,1} & z_{2,2} & z_{2,3} \\ z_{3,1} & z_{3,2} & z_{3,3} \end{pmatrix} \tag{5}$$

and the note term of the system (4) gives:

$$\hat{V}^t\hat{Y} = \begin{pmatrix} 1 & 1 & 1 & \dots & 1 \\ \hat{x}_0 & \hat{x}_1 & \hat{x}_2 & \dots & \hat{x}_8 \\ \hat{x}_0^2 & \hat{x}_1^2 & \hat{x}_2^2 & \dots & \hat{x}_8^2 \end{pmatrix} \begin{pmatrix} \hat{y}_0 \\ \hat{y}_1 \\ \hat{y}_2 \\ \vdots \\ \hat{y}_8 \end{pmatrix} = \begin{pmatrix} d_1 \\ d_2 \\ d_3 \end{pmatrix}. \tag{6}$$

Finally, substituting (5) and (6) in (4), it gives the following square matrix system:

$$\begin{pmatrix} z_{1,1} & z_{1,2} & z_{1,3} \\ z_{2,1} & z_{2,2} & z_{2,3} \\ z_{3,1} & z_{3,2} & z_{3,3} \end{pmatrix} \begin{pmatrix} a_0 \\ a_1 \\ a_2 \end{pmatrix} = \begin{pmatrix} d_1 \\ d_2 \\ d_3 \end{pmatrix} \tag{7}$$

whose solution allows the assessment of the coefficients a_0, a_1 and a_2 and then attainment of the 2nd order least-squares polynomial (2).

At the end of the calculations, for each performance parameter, the residuals average e was evaluated through the following equation:

$$e = \frac{1}{9}\sum_{i=1}^{9}(\hat{y}_i - y_i) \tag{8}$$

3. Results and Discussion

In Table 1, all the obtained experimental data corresponding to each of the considered gear-range lever combinations, screw conveyor angular speeds and repetitions are reported as follows: (i) tractor–harvester aggregate forward speed V, m·s^{-1}; (ii) tractor PTO required torque T_{PTO}, N·m; (iii) traction force R, N; (iv) tractor PTO required power N_{PTO}, kW; and (v) total required power measured at the tractor rear drive axle N, kW.

Table 1. Beet top harvester obtained experimental data.

Tractor Gear-Range Lever	V, m·s^{-1}	T_{PTO}, N·m	R, N	N_{PTO}, kW	N, kW
ω_{po1} = 57 rad·s^{-1}					
1st gear-high speed ratio	0.990	91.35	1092.2	5.165	1.081
	0.960	97.15	1244.6	5.493	1.194
	0.954	92.8	914.4	5.247	1.272
2nd gear-low speed ratio	1.464	97.15	1447.8	5.493	2.119
	1.380	101.5	1625.6	5.739	2.242
	1.524	117.5	1727.2	6.644	2.631
3rd gear-high speed ratio	2.118	168.2	1803.4	9.511	3.818
	2.196	169.7	1930.4	9.596	4.238
	2.022	162.4	1727.2	9.183	3.491
ω_{po2} = 39 rad·s^{-1}					
1st gear-high speed ratio	1.014	60.9	1244.6	3.444	1.261
	1.146	71.05	1193.8	4.017	1.367
	1.176	66.7	1346.2	3.772	1.582
2nd gear-low speed ratio	1.698	81.2	1574.8	4.591	2.673
	1.536	71.05	1295.4	4.017	1.989
	1.722	78.3	1701.8	4.427	2.929
3rd gear-high speed ratio	2.124	111.7	2108.2	6.316	4.476
	2.220	156.6	1549.4	8.855	3.438
	2.058	142.1	1955.8	8.035	4.024
ω_{po3} = 0 rad·s^{-1}					
1st gear-high speed ratio	1.140	50.75	1041.4	2.870	1.186
	1.236	60.9	1320.8	3.444	1.632
	1.314	66.7	1117.6	3.772	1.468
2nd gear-low speed ratio	1.692	71.05	1473.2	4.017	2.492
	1.746	58.00	1295.4	3.280	2.261
	1.614	59.45	1625.6	3.362	2.623
3rd gear-high speed ratio	2.256	89.9	1752.6	5.083	3.953
	2.166	97.15	1981.2	5.493	4.290
	2.148	85.55	1752.6	4.837	3.763

ω_{po1}, ω_{po2}, ω_{po3}: screw conveyor drive shaft angular speeds.

Table 2 reports second order polynomial regressions with the corresponding R^2 values and residuals for the assessed performance parameters; the response variables are the torque T_{PTO} and the power N_{PTO}, the tractor traction force R, and the total tractor power N, respectively. The explanatory variable is the aggregate forward speed. These regression functions are plotted in Figures 5–7.

Table 2. Second order regression results of different V dependent parameters.

	Screw Conveyor Drive Shaft Angular Speed		
	ω_{po1} = 57 rad·s^{-1}	ω_{po2} = 39 rad·s^{-1}	ω_{po3} = 0 rad·s^{-1}
R *	$R = -264.003 \cdot V^2 + 1433.064 \cdot V$ $R^2 = 0.8661 - e = -3.048$	$R = -238.756 \cdot V^2 + 1366.048 \cdot V$ $R^2 = 0.6589 - e = 1.246$	$R = -121.706 \cdot V^2 + 1090.533 \cdot V$ $R^2 = 0.7845 - e = 0.538$
T_{PTO}	$T_{PTO} = 54.410 \cdot V^2 - 104.234 \cdot V + 143.073$ $R^2 = 0.9709 - e = -0.001$	$T_{PTO} = 90.495 \cdot V^2 - 224.716 \cdot V + 202.692$ $R^2 = 0.8969 - e = 0.001$	$T_{PTO} = 32.815 \cdot V^2 - 78.774 \cdot V + 104.929$ $R^2 = 0.8238 - e = 0.000$
N_{PTO}	$N_{PTO} = 3.0769 \cdot V^2 - 5.8944 \cdot V + 8.0899$ $R^2 = 0.97092 - e = 0.0000$	$N_{PTO} = 5.1190 \cdot V^2 - 12.7129 \cdot V + 11.4660$ $R^2 = 0.89686 - e = -0.0001$	$N_{PTO} = 1.8552 \cdot V^2 - 4.4539 \cdot V + 5.9337$ $R^2 = 0.82376 - e = -0.0001$
N *	$N = 0.4746 \cdot V^2 + 0.8380 \cdot V$ $R^2 = 0.98197 - e = -0.0037$	$N = 0.5623 \cdot V^2 + 0.6372 \cdot V$ $R^2 = 0.89571 - e = -0.0026$	$N = 0.6672 \cdot V^2 + 0.3490 \cdot V$ $R^2 = 0.94897 - e = -0.0001$

* Provided that the regression lines pass through the coordinates' origin.

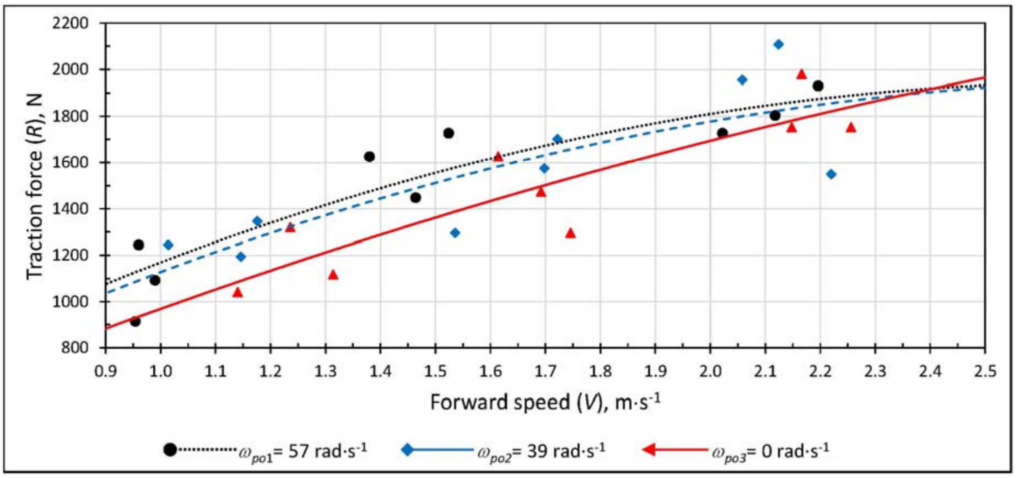


Figure 5. Tractor traction force R vs. aggregate tractor–beet top harvester forward speed V for different values of screw conveyor drive shaft angular speed.

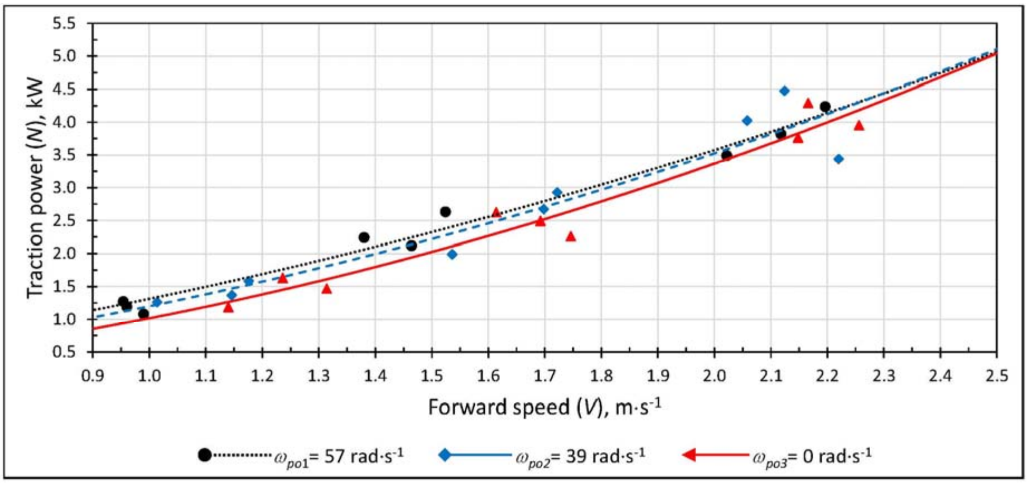


Figure 6. Tractor traction power N vs. aggregate tractor–beet top harvester forward speed V for different values of screw conveyor drive shaft angular speed.

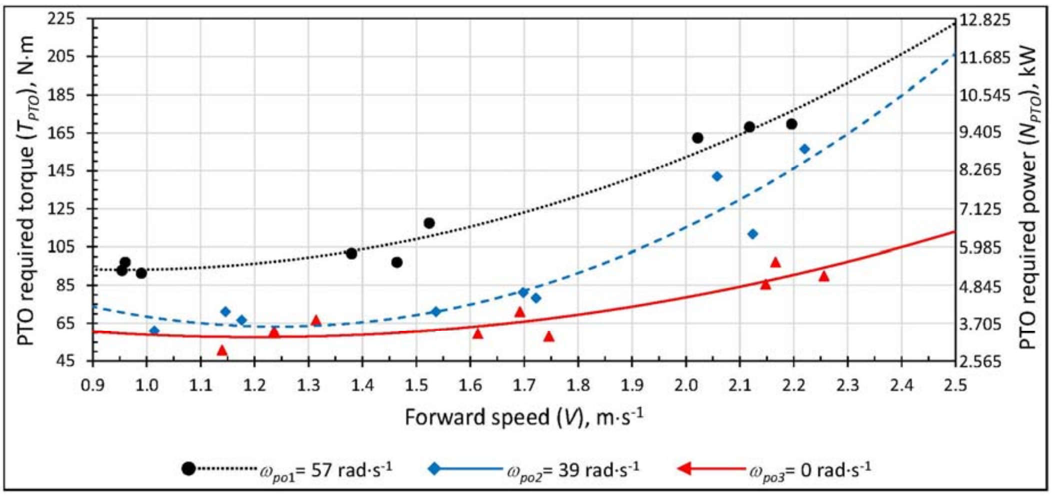


Figure 7. PTO required torque T_{PTO} and power N_{PTO} vs. aggregate tractor–beet top harvester forward speed V for different screw conveyor drive shaft angular speeds.

The traction force required by the tractor was not so much influenced by the screw conveyor drive shaft angular speed and, even if its increase was almost 94% in the considered aggregate forward speed range (Figure 5), in absolute terms the increase was of only almost 1 kN. This behavior can be explained by considering that the tractor traction force is mainly the sum of the wheels rolling resistance and the push force required by the front beet topper machine. As is known, the rolling resistance of tires on a surface is mainly connected to the hysteresis in tire materials caused by the deflection of the tire casing during rolling as well as by its operating conditions, such as surface conditions, inflation pressure, rolling speed, temperature, and so on [49,50]. Nevertheless, in the considered speed range, that is within 0.9 and 2.5 m·s^{-1}, the tire's rolling resistances can be considered almost constant and the low absolute increase in the traction force is probably due to the increase in the flow rate of tops that have to be processed by the cutting apparatus as the aggregate forward speed increases [27,29]. Therefore, according to other studies, the tractor traction force is affected by the speed of the aggregate, rather than by the screw conveyor drive shaft angular speed variations [23,31]. In the above-mentioned speed range, the traction force varies from 1.1 to 1.9 kN, considering $\omega_{po1} = 57$ rad·s^{-1}.

Figure 6 shows how the traction power measured at the tractor's rear drive axles increased within the range of 0.81–5.0 kW as the aggregate forward speed increased and also, for this parameter, no significant dependency related to screw conveyor drive shaft angular speed variations appeared.

Referring to the relations between the required torque, the power at the tractor PTO shaft and the aggregate forward speed evaluated for different screw conveyor drive shaft angular speeds, as shown in Figure 7, there was limited growth of the interested parameters for an increase of the forward speed up to about 1.5 m·s^{-1}. For higher speed values, an important increase of the required torque and power can be observed. Furthermore, the screw conveyor drive shaft angular speed had a significant effect on the PTO required torque and power values. At an angular speed of $\omega_{po1} = 57$ rad·s^{-1}, the required torque (power) was 93.3 N·m (5.3 kW), and at a forward speed of 0.9 m·s^{-1}, this increased by 139% to 222.6 N·m (12.6 kW) at a speed of 2.5 m·s^{-1}. Whereas when the screw conveyor is turned off $\omega_{po3} = 0$ rad·s^{-1}, the required torque (power) increased by 86.7% from 60.6 N·m (3.4 kW) at a forward speed of 0.9 m·s^{-1} to 113.1 N·m (6.4 kW) at a speed of 2.5 m·s^{-1}. This behavior is clearly connected to the greater product flow rate that the cutting apparatus must process as forward speed increases.

Taking into account both the $N(V)$ and $N_{PTO}(V)$ relationships between the tractor power, PTO required power and aggregate forward speed represented in Figures 6 and 7, it is possible to assess that the entire technological process of the harvesting and transporting to the storage unit of the beet tops requires a power which ranges from 6.42 to 17.65 kW (with $\omega_{po1} = 57$ rad·s^{-1}). However, in normal operating conditions with a forward speed ranging from 1.7 to 2 m·s^{-1}, the total required power ranges from 10 to 12 kW.

During the tests, the lower screw conveyor drive shaft angular speed ($\omega_{po2} = 39$ rad·s^{-1}) ensured the proper performance of the harvesting machine. Nevertheless, in the case of increased humidity or an excessive amount of weeds on the field, congestions and obstructions occurred in the screw conveyor operation. According to the experimental results, the suitable screw conveyor drive shaft angular speed has to be in the range of 50 to 60 rad·s^{-1} so the chosen angular speed $\omega_{po1} = 57$ rad·s^{-1} can be a guarantee of reliability in all operating conditions.

The executed field tests carried out using the new beet top harvesting machine also highlighted that its average energy costs, related to a single work row (N_{PTO} = 3.1 kW and N = 1.4 kW), are significantly lower than the corresponding performance parameter values of beet top harvesting machines currently in use on Ukrainian farms.

4. Conclusions

Sugar beet is a temperate climate crop which is grown profitably in almost all areas of the world with latitudes over than 30° where the winters are not very hard. Obviously, cultivation systems and material inputs must be adjusted according to the climate and soil characteristics, taking into account that the quality of the beet deeply affects the operative efficiency of the process carried out inside a sugar beet factory. During the harvesting operations, the cut off and collection of the beet tops must be performed properly with suitable machines. The new front-mounted beet topper machine analyzed in this study is able to process three-rows of beets simultaneously, under conditions of high quality performance of the technological process. The results of the executed test highlighted its good performance, pointing out that the tractor power and its traction force, as well as the torque and the power required at its power take-off, are on average 1.2 to 1.5 times lower than the corresponding performance parameters of the beet top harvesters currently employed in Ukraine. Nevertheless, further technical improvement of the screw conveyor system is under study in order to make better the efficiency of the system that allows the transport and loading of cut beet tops. Further experimental campaigns will be then necessary to re-verify the performance parameters analyzed in this study.

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